PRINCIPLES

OF

DYNAMO-ELECTRIC MACHINES

AND

PRACTICAL DIRECTIONS FOR DESIGNING
AND CONSTRUCTING DYNAMOS.

WITH AN APPENDIX CONTAINING SEVERAL ARTICLES ON ALLIED SUBJECTS AND
A TABLE OF EQUIVALENTS OF UNITS OF MEASUREMENT.

BY

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PREFACE.

ENGINEERS and machinists practically engaged in designing, constructing and repairing dynamos, as well as amateurs, students of electrical engineering and electrical artisans, frequently find it difficult either to understand the true principles of the dynamo or to deduce the proper proportions, from the information contained in existing text-books. This arises chiefly from the fact that much of the valuable information given by physicists unfortunately is not always in the form in which it may be practically applied by the engineer. No doubt also many lack that knowledge which is not usually found in text-books, and which is obtained only from actual experience with dynamos.

To meet these needs, the author has endeavored to give in a concise and simple form the information most required by those using, building or repairing dynamos. In doing so it has not been thought necessary to preface the book with an elementary treatise on electricity in general, as this is already contained in numerous text-books; the author pre-supposes, on the part of the reader, a general knowledge of the subject of electricity and its applications, that which is contained in this book being limited chiefly to details of the practical application of these principles to the designing, construction and care of dynamos. The book is therefore intended more particularly for builders and attendants of dynamos, amateurs and students. It is needless to say that it is not intended for experts, physicists or theorists, nor for those who have the facilities and time to search for such information in the more advanced publications.

Abstruse theories of dynamos have been entirely omitted as being of little use to the practical engineer. Until such theo-

ries have been thoroughly tested by repeated and varied applications in practice, and are reduced to such a form that they may be readily applied, the constructor of dynamos is recommended to use the well tried but less direct methods. Probably the best among the newer methods of designing magnets for dynamos, and one which appears to be an important improvement in the right direction, is that proposed by Mr. Gisbert Kapp, in the *Proceedings of the Society of Telegraphic Engineers*, November 11th, 1886, and subsequent papers, to which the more advanced readers are referred.

It is assumed, in this book, that the reader has a knowledge of arithmetic and understands the application of simple formulæ. All formulæ, laws and relations are given in as simple forms as are consistent with clearness, but it is possible that in doing this the author may sometimes have sacrificed strict scientific accuracy; it was thought, however, that as the calculation of the parts of dynamos does not admit of absolute precision, this would not be objectionable.

The subject matter of this volume first appeared as a serial in the *Electrician and Electrical Engineer*, of New York, but it has been revised in numerous parts. The Appendices contain several papers by the author on allied subjects (Appendix IV being only an abstract of the original), which were also published in the above Journal, and which it is thought might be of use to the readers of this book. To the table of equivalents have been added those of work, power and heat, besides numerous others, making it more nearly complete.

CARL HERING.

University of Pennsylvania,
February, 1888.

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OF

DYNAMO-ELECTRIC MACHINES.

CHAPTER I.

Review of Electrical Units and Fundamental Laws.

Electrical phenomena, being, like all other, resultants of force and matter, are in many respects quite analogous to mechanical phenomena. Their nature may therefore, in many cases, be much more readily understood by comparing them with well-known mechanical effects. Understanding the mechanical relations, it is then very easy to understand the electrical ones by their analogy. The necessary electrical computations will then be much more readily intelligible and will appear quite as simple, and perhaps even more simple, than the ordinary mechanical ones.

Unlike in mechanical phenomena, the quantities in electrical computations are not measured in pounds, feet, or gallons, by reason of the different nature of the forces and matter; they must, therefore, be measured in units of their own. Although electrical phenomena are not expressed in pounds, feet or gallons, it is quite admissible to say that there are quantities in electrotechnics which have similar functions to distance, weight and capacity in mechanics, and that the analogies to these may be used to illustrate the nature of different electrical phenomena and to assist in showing how electrical calculations should be made.

This may be best shown by an example. The ordinary well-known centrifugal blower, consisting simply of a number of fans rotating in an enclosed vessel, will, when in action, produce a compression of the air at one part, and

a rarefaction of air at another; that is, it will force the air out at one part, and draw it in at the other. If the two ends of a tube are attached to these two points, a current of air will be caused to flow through it in a definite direction. This very simple machine affords a very good illustration not only of the simple quantities in electrotechnics and the elementary laws of electrical action, but also of other points which are less frequently well understood, and by a clear conception of which, electric batteries, machines and phenomena connected with them, appear much simpler, and can, therefore, more readily be subjected to quantitative investigation.

The mechanical pressure of air which is generated in the blower, being of a positive character (having a density greater than that of the atmosphere) at one part, and negative (or suction, or less than the atmosphere) at another part, corresponds precisely to the electrical pressure, or *potential*, in batteries and machines. In both cases, if they are allowed to equalize themselves, they will produce a current in a certain direction—from the positive to the negative in the external circuit, and from negative to positive within the machine or battery itself. This pressure, which in mechanics is expressed as so many pounds per square inch, corresponds in electrotechnics to what is termed electrical pressure, electromotive force, potential, or tension, and which is measured in volts.

In the case of air, the zero or normal pressure corresponds with that of the atmosphere, for when air in a confined vessel is at atmospheric pressure, there will be no current produced if the vessel is made to communicate with the air. In the case of water, the zero level is taken as that of the ocean. Similarly there is a zero level or pressure of electricity with which other pressures can be compared. This is the natural pressure of electricity in the earth itself. The earth, as is well known, may be regarded as a reservoir of electricity of infinite quantity, and its pressure is taken as zero. If one pole of a battery or other generator

is connected with the earth and a current tends to flow from it to the earth, then that pole is assumed to be positive; and if the other pole be similarly connected, the current will tend to flow from it to the generator, and is therefore assumed to be the negative pole. As almost all electric lighting apparatus is isolated from the earth, it makes no practical difference whether the actual pressure is above or below zero. All that concerns the electrician is to know what is the difference between the two pressures at the two poles of the battery or other generator; hence the term "difference of potential." The zero pressure of electricity is, however, important in considering ground connections of machines and lines, as will be seen hereafter.

As in mechanics a pressure is necessary to produce a current of air, so in electrical phenomena an electromotive force is necessary to produce a current. A current in either case can never exist without a pressure to produce it. From this the important law is deduced that a difference of electrical pressure cannot exist at two points of a conductor without generating a current between these two points, except when there is a counter pressure in that conductor in the opposite direction, as, for example, in the machine itself. This law, which seems self-evident, is frequently of use in solving certain problems.

This current of electricity, expressed in ampères, represents quantity per second, just as it would do in an air current, and it is very similar in many other respects to the current of air produced by a blower.

The actual quantity of electricity itself is measured in coulombs, which correspond to quantity of air. Just as in the case of air, this quantity may exist in a state of rest, as in the charge of a Leyden jar, or a charged cloud; and in that state it may be at any pressure, either greater or less than that of the earth. If in that state it is allowed to equalize itself, through a conductor to the earth or to another confined quantity of electricity at any other pressure, a current will flow as in the case of air. If this quan-

tity be limited, as in a statically charged Leyden jar or condenser, it will equalize itself suddenly in the form of a momentary current or spark, in the same way as the confined gases of ignited powder in a pistol suddenly equalize their pressure with that of the atmosphere. If, however, this pressure, which is consumed, be continually replaced by some means, in the same proportion in which it is consumed, the current which was momentary in the first case will then become continuous. This is precisely what is done by an electric machine, battery, or other generator. It continually replaces the electrical pressure which is consumed or equalized through the lamps and conductors connecting its poles, just as the centrifugal blower continually replaces the pressure which is again consumed in the place where it equalizes itself or where the work is done.

It will be seen from this that the object of an electric machine, battery or other generator, is to maintain a continuous electrical pressure, or electromotive force, the amount of which shall be equal to that which is consumed, for in that case only can a continuous current be established and maintained. Properly speaking, its object is not to generate electricity, for there is practically an infinite quantity of that in the earth itself, and were it only the quantity of electricity which is wanted, there would be no need of machines. Electricity in quantity without pressure is useless, for it cannot be made available, under such conditions, for operating lamps, telegraphs, etc. It is a current which is required, and this can be maintained only by a constant renewal of pressure, which is what the machine, battery, or other generator does. As electricity is neither consumed in lamps nor actually generated by machines, it follows that to each electric machine or battery there must be two conductors or wires—one to lead to it the supply of electricity at low pressure, and the other to lead off the electricity of high pressure, while on the other hand, in the lamps or other apparatus, where the pressure is consumed, the function of the wires is precisely the reverse.

The truth of the proposition that electricity is not actually produced in the machines nor consumed in the lamps, may be demonstrated by measuring the actual quantity of current flowing in through one wire and out through another, which will always be found the same. The action is precisely analogous to what takes place in the centrifugal air blower, which, as we well know, generates pressure, but not air. It may also be compared to a hydraulic pump, which generates the pressure of the water, but not the water itself; as much water must flow into the pump at one end as flows out at the other.

From these remarks the following important laws become self-evident:

As the pressure, and not the electricity, is that which is produced and consumed, it follows that the current strength is always the same in every part of a given circuit. In case the circuit is divided at any point, the sum of the divided currents is always equal to the undivided current in the rest of the circuit. The function, therefore, of an electric machine or battery, is to *generate and maintain an electromotive force*, or electrical pressure. Whenever this pressure is allowed to act or to equalize itself, a *current* of electricity will be produced.

The electrical resistance (measured in ohms) which opposes the current, is also quite analogous to the mechanical resistance which must necessarily be encountered by every current of air. The only difference is that the electrical resistance depends only on the cross section, length, and nature of the material of the conducting medium, while with a current of air the resistance is affected by certain other factors, thus making calculations due to electrical resistance much the more simple of the two.

The laws of resistance are very easy to understand. Electrical resistance increases in the direct ratio of the length and decreases in the ratio of the area of cross section. It also depends specifically upon the nature of the material, or in other words, on a particular constant for each

substance. It also increases with the temperature in metals and decreases in carbon and liquids. The unit of resistance now universally adopted is the Paris or legal ohm, which is the resistance of a column of pure mercury of one square millimetre cross section and 106 centimetres in length, at a temperature of 0° C. The Siemens unit is the same except that the column is 1 metre long. The old unit formerly used is called the British Association (B. A.) unit. Their equivalents are as follows:

1 legal ohm	=	1.0112 B. A. units.[1]
1 B. A. unit	=	.9889 legal ohms.[1]
1 Siemens unit	=	.9434 " "
1 legal ohm	=	1.0600 Siemens units

The very simple relation which exists between the electrical pressure or electromotive force, the resistance and the resulting current, forms the basis of almost all electrical computations and is known as Ohm's law. This law is nothing more than a statement of the fact that the result of any action increases when the cause of action increases, and decreases when the force opposing this action increases. As we have seen, the electrical pressure or electromotive force is the cause which produces a current, without which a current cannot possibly exist. We have also seen that the resistance opposes this current, and therefore opposes the action of the pressure, or cause of the current. Therefore the resultant of both of these will be the current. Or stated in more concise terms, the resulting current is equal to the electromotive force divided by the resistance.

From this well-known law two others necessarily follow, which are equally useful, though, strange to say, less frequently used. One serves to determine what pressure or electromotive force is required to produce a certain current through a certain resistance. It follows from the law above given that this electromotive force will be the product of

1. As marked on the standard legal ohms, by Mr. Glazebrooke, secretary of the British Association.

the given resistance and the given current. The other enables us to find what resistance is to be inserted in order that a given electromotive force shall produce a certain current. This resistance will be readily seen to be equal to the electromotive force divided by the current.

Another very important law follows from the above-mentioned premises. If a current divides at any point into two or more lesser currents, it follows that each of these divided or fractional currents will be greater in proportion as the resistance of its own circuit is less, or in other words, each current will be proportional to the reciprocal of its resistance. It is also self-evident that the sum of the divided currents will be equal to the total undivided current. If the difference of the electrical pressure or potential, at the points where the current divides and joins again, is known (as in a dynamo machine), the calculation becomes exceedingly simple, as it then is merely a double application of one of the laws above given, namely, that the current in each branch is equal to the difference of potential divided by the resistance of that branch.

The only quantities, besides *time*, which are of the same kind in both electrotechnics and mechanics, are *energy* or *work*, and *power*. These are, therefore, the connecting links between the two, and are the quantities to which both must be reduced, in order to find how much of the one will be equal to a given quantity of the other.

In mechanics it is well known that work is measured in foot-pounds, while power (which is merely an amount of work done in a certain time or rate of doing work) is measured in horse-powers.

If a certain quantity of air, for instance a cubic foot, at ordinary pressure, is compressed, say to half that quantity, or what is the same thing, to double that pressure, a certain definite number of foot-pounds of energy will be required, and if it be allowed to expand again, that is to equalize the pressure again with the atmosphere, that same amount of work in foot-pounds will be given off. It will be equal to

the pounds mean pressure multiplied by the distance through which it acts, in feet.

In precisely the same way, when a certain quantity of electricity in coulombs has its electrical pressure increased a certain number of volts, a certain definite amount of work will be required, which is measured in volt-coulombs. When this same quantity at high pressure is allowed to decrease its pressure again, that same amount of work in volt-coulombs will again be given off, just as in the case of the air. A volt-coulomb is often called a joule.

As in the case of air, if the quantity of electricity be doubled, the work will be doubled, or if the pressure be doubled the work will be doubled; in other words, the work in electrical units will be the number of volts pressure through which it has been raised or through which it has fallen, multiplied by the quantity in coulombs which have been subjected to this change of pressure. The electrical energy is, therefore, merely the number of volts multiplied by the number of coulombs.

The same equality exists between electrical and mechanical power. As a horse-power is merely a certain number of foot-pounds of work done per second, so electrical power is a certain number of volt-coulombs of work done per second. As a coulomb of electricity flowing per second is an ampère of current, it follows that a volt-coulomb of work per second is a volt ampère, or, as it is frequently called, a watt, from which it follows that volt-ampères, or watts, and horse-powers are units of precisely the same kind and may be reduced from one to the other.

In order, therefore, to calculate the electrical power in a circuit, lamp, or machine, it is only necessary to multiply the volts pressure by the ampères of current. This law, combined with Ohm's law, gives two more equally important laws in regard to electrical power. When the electromotive force and the resistance are given, the power in volt-ampères or watts is equal to the square of the electromotive force divided by the resistance; *i. e.*, if with the same

electromotive force the resistance is doubled, the power is halved; or if with the same resistance the electromotive force is doubled, the power is increased four times. The other law is that when the current and resistance are given, the power in volt-ampères or watts is equal to the square of the current multiplied by the resistance. That is, if, with the same current, the resistance is doubled, the power is doubled, or if, with the same resistance, the current is doubled, the power is increased four times.

This last law is often stated in a very misleading way in text books and by many scientists, whose lack of clearness in statement is often very annoying to practical engineers. Thus we find it stated that the energy is proportional to the square of the current. This is not only misleading, but in many cases absolutely false. The current may be increased, while the total energy may be the same, or greater, or less, depending on the electromotive force or the resistance. The current itself is no criterion, for it might as well be said that the current of water in a river represents horse-power. If the fall of the water is not taken into account, or in electricity the electromotive force or resistance, the current by itself is no measure of the power developed. It will be readily seen that if the current be doubled by halving the resistance (the electromotive force remaining the same), the energy will be increased twice as much, and not four times. In another case, if the electromotive force be reduced to one-quarter and the resistance reduced to one-eighth, the current would evidently be doubled, while the energy would really be only half as great.

The law just given is correct only in one case, that is, when the resistance remains the same. The power then increases with the square of the current, for in order to double the current in the same resistance, it is necessary to double the electromotive force, thus doubling both volts and ampères, quadruples the volt-ampères.

The so-called absolute system furnishes us with a means

of finding the actual quantities of foot-pounds or horse-powers which correspond to a volt-coulomb or volt-ampère. These values are as follows: [2]

1 volt-coulomb	=	.73732 foot-pounds.
1 foot-pound	=	1.3563 volt-coulombs, or joules.
1 watt	=	.0013406 horse-power.
1 horse-power	=	745.941 volt-amperes, or watts.

If a pound weight be dropped freely through a distance of 1,000 feet, or if 1,000 pounds be dropped through a distance of 1 foot, the quantity of work will be precisely the same in each case, namely, 1,000 foot-pounds. But at the same time the quality or kind of work will be quite different. Or if in one case a small quantity of air under high pressure, and in another case a large quantity of air under low pressure, be allowed to escape, the actual amount of work done might be the same, yet the quality or kind of work or effect would be quite different. Similarly, if a coulomb of electricity is allowed to change its potential suddenly 1,000 volts, or if 1,000 coulombs be allowed to fall through a potential of one volt, the actual quantity of work in volt-coulombs will also be the same; yet in the two cases the form or quality of the energy dissipated would be quite different. Many electrical phenomena in which electrical energy is dissipated can, therefore, be much more readily understood by comparing them to air under compression, the pressure being proportional to the electrical pressure and the quantity proportional to the quantity of electricity. This will readily answer the question frequently asked, "what is the difference between the electricity of a friction or influence machine, or Rhumkorff coil, or lightning, and that produced by batteries, dynamos, and used in telegraphy, telephony and electric lighting?" The difference is merely in the form or quality of the energy dissipated.

2. For the method of calculating them, and for a complete set of equivalents, see THE ELECTRICIAN, vol. ii., p. 103 (April, 1883, New York); also Appendix V.

There is also a similarity between the different forms in which power exists. For instance, if a pound weight be dropped freely through a distance of 1,000 feet, or if it be allowed to fall slowly, as when driving a clock; in both cases the work will be the same, but as the time in which it is done in the two cases is quite different, the power will be different. In the same way, if a quantity of elastic gas confined under high pressure be allowed to escape suddenly, as in firing a cannon, or allowed to escape slowly, as in a small compressed air engine, the quantity of work may be the same, yet the kind or quality will be very different. Similarly, if a quantity of electricity at high pressure or electromotive force be allowed to dissipate its energy suddenly, as in a spark or bolt of lightning, or if it be consumed gradually, as in the telegraph or electric light, the quantity in volt-coulombs may be the same, yet the power in volt-ampères will be quite different.

In still another case the power might be the same in the two cases, yet its quality or kind may be very different. For instance, a very high waterfall with small quantity of water, on the one hand, and a sluggishly flowing river with small fall, on the other hand, may each develop precisely the same available horse-power, yet the quality of their power, and therefore the apparatus necessary to effect its conversion, will be quite different. This is analogous to a dynamo of high electromotive force and small current, such as is used for arc lighting, and another of low electromotive force and great current, such as is used for electroplating; they may both require the same horse-power, yet the form of the electrical power is different.

A few quantitative examples, illustrating what has been said above, may be of interest. The pressure of ignited gunpowder being about 40 tons per square inch, the energy in a bullet fired from a small pistol is about 600 foot-pounds. As a pocket watch consumes about one fifty-four millionth of a horse-power, it follows that the amount of energy in the bullet would run the watch almost two years.

As the current in an Edison telephone transmitter was found to be about .0001 ampère,[3] and its resistance about 1 ohm, the energy in it is slightly less than one-thousandth part of that used in a watch, and it would therefore be run over 2,000 years with this same amount of energy as developed in a small pistol.

The charge of a small Leyden jar was found to be .000,008 coulombs at about 50,000 volts. This in discharging would develop .4 volt-coulombs, or .288 foot-pounds of energy, which would run a watch about eight hours, and is about equal to double the amount of energy consumed per second in the line of a telegraph circuit of 100 miles.

Several authorities have calculated the electromotive force of a bolt of lightning to be about 3,500,000 volts, and the current to be about 14,000,000 ampères, the time of the bolt being measured to be one twenty-thousandth of a second. A simple calculation shows that this amount of energy set free in that short time is about as much as that of a 100 h. p. engine for almost 10 hours.

Besides the electrical units above mentioned, there are certain others less frequently used.

Capacity in electrotechnics is very similar to capacity in mechanics. Although it cannot be measured in cubic inches or quarts, yet its function, which is to measure quantity, is the same as in the ordinary sense. Just as a quart measure may hold a certain amount of air at atmospheric pressure, or double that amount (by weight) at two atmospheres, and so on, so does an electrical condenser, having a certain electrical capacity, hold a certain definite amount of electricity at a certain electrical pressure or electromotive force, and double this amount at double the pressure, and so on. Any amount of electricity can be forced into a condenser of a given capacity by increasing the pressure in proportion, in the same way that any quantity of air (by weight) can be forced into a quart measure by simply increasing the pressure accordingly.

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3. See ELECTRICIAN AND ELECTRICAL ENGINEER, Nov., 1885, vol. iv., p. 422.

From this the law in regard to capacity becomes self-evident. The quantity of electricity in coulombs in a given condenser, divided by its pressure in volts, is always a constant, and is equal to the capacity of the condenser in *farads* or units of capacity.

Two other laws follow from this, namely, that the quantity of electricity in a condenser is the capacity multiplied by the pressure or electromotive force. And lastly, the pressure or electromotive force of the electricity in a condenser is equal to the quantity of electricity divided by the capacity of the condenser.

Ampère-hour is a convenient term for representing 3,600 coulombs, as it is equal to an ampère flowing for one hour, and is used in connection with the accumulation of electrical power in batteries.

Ampère-winding or ampère-turn, used in reference to electro magnets and solenoids, represents an ampère of current circulating once around the coil. The number of windings or turns of wire in a coil, multiplied by the current in the wire, gives the number of ampère-turns of the whole coil. As will be seen hereafter, it is a term used for representing, measuring and calculating the magnetism of machine magnets.

Electrical horse-power is merely the number of volt-ampères which equal a mechanical horse-power, as given in the table on page 10.

CHAPTER II.

Fundamental Principles of Dynamos and Motors.

THE explanations which are given in many text-books of the process of generating electric currents in the dynamo machine, and the production of mechanical power in the electric motor by means of the electric current, are in many cases unsatisfactory. This is largely due to the failure of the authors to lay down any fundamental principle, applicable alike to all kinds of machines. The principles involved are often explained in an indirect and circuitous way, and in one well-known work recently published, the explanation of the manner in which the currents are generated in a Gramme ring armature are not merely misleading but absolutely erroneous, and are in fact inconsistent with actual results which may be obtained even from a rough test.

In attempting an explanation of the principle of the dynamo, we propose therefore, to discard insufficient and erroneous theories, and to take for our starting point the fundamental law illustrated in the action between a magnet and a current, as conclusively demonstrated by one of the most simple of experiments. By so doing it will be found that the generation of currents and of power in dynamos and motors may be explained by simple and direct methods, while at the same time the general directions which should be pursued to obtain the most economical proportions are pointed out.

In the year 1819, Hans Christian Oersted, a Danish philosopher, discovered that a current of electricity when caused to pass near a magnetic needle will deflect it. Or, in other words, he discovered that an electric current and a magnet exert a mutual force upon each other. This simple experiment is a demonstration of the fundamental principle of all dynamos and motors; by its means the

generation of currents or power in all the different types of machines may be rendered easily intelligible without the intervention of abstruse or complicated theories, which in many cases have to be in themselves varied to correspond with the facts observed in various types of machines.

All electric motors are nothing more than direct applications of this principle on a large scale, for whatever is true of a small magnetic needle and a weak current, is equally true, in principle, of a large magnet and a powerful current. Every motor will be found upon analysis to consist of one or more magnets and a conductor traversed by a current of electricity, one of the two, or both, being capable of receiving a continued motion from the mutual force exerted between the magnet and the current, as shown in Oersted's experiment. The movable conductor may be in the form of one or more straight wires, or it may be a coil, or, as in a unipolar motor, a disc or hollow cylinder. In each of these modifications the operative principle remains the same, that is, simply the mutual action between the magnet and the current.

In electric motors this principle applies directly, as these are merely practical devices for carrying out Oersted's experiment on a large scale under such mechanical conditions as to obtain constant rotary motion. In the case of dynamos, however, a deduction from this principle applies, for while in motors the exact conditions of Oersted's experiment exist, in generators the magnet and the mechanical force are given, the resulting current being that which is required. The explanation of the action of generators, however, offers no additional difficulties, as the converse of Oersted's experiment is also true, namely, that if the conditions of that experiment be reversed, by moving the conductor in the reverse direction, a current will tend to be generated in that conductor, or, as it is generally stated, a current will be *induced* in that conductor, which is then termed the *inductor*. This is commonly known as one of Lenz's laws, which, stated in more precise terms, is

this: *If a conductor be moved near a magnet it tends to generate a current, which will flow in the opposite direction to the current which would, by its action on the magnet, produce that motion.*

This may be further illustrated by analogy. Between the earth and a body held at some distance from it, there exists a force, which if allowed to act, will draw the body to the earth. Now if this is reversed by overcoming the force and lifting the weight, the amount of energy which was used in lifting it will again be stored up in the weight. Or, in other words, if the process of the falling weight is reversed, the same energy which was set free in falling will be generated again in the body. Similarly if Oersted's experiment, or the electric motor, be reversed by moving the conductor near the magnet in the opposite direction, the same amount of current will be generated that would have been necessary to produce this motion. As in the case of the weight, in which the energy developed in falling is equal to that required to raise it, so in electric induction, the current generated by moving the wire is theoretically equal to that which is required to produce that motion. For instance, if a certain amount of electrical energy in a movable conductor exerts a force or tendency to move in a certain direction, equal to one pound, on a large magnet, then it would require a force of one pound to generate that same amount of electrical energy in that conductor by moving it in the opposite direction.

These are the fundamental principles underlying the construction of all dynamos and motors, and by means of which the action in all of them may be explained, be they constant current, alternating current, unipolar, bi-polar or multi-polar. They all consist of a magnet and a conductor for the current, one or the other, or both of which are movable, as in Oersted's experiment.

In the explanation, just given, it was said that a *current* is generated by moving a wire in the vicinity of a magnet. It must be remembered, however, as pointed

out in the first chapter, that a current is merely the result of the equalization of a difference of electrical pressure. Strictly speaking, therefore, it is not actually current but *electromotive force* or electrical pressure, which is generated by the induction in the moving wire, for by disconnecting or opening the circuit, it will be found that the electromotive force still exists, even if no current can flow. The word *current* was used merely for the sake of avoiding a multiplicity of terms in the explanation. A current does exist in most cases, but its existence is due only indirectly to induction. Its actual origin is due to an equalization of the electromotive force which has been generated by induction. As pointed out in the first chapter, it is quite similar to the case of a centrifugal air-blower, in which the *pressure* is that which is generated, the current being only a secondary result of this pressure. This conception of induction will be found to materially simplify the conception and solution of many problems which are met with in practice, as, for instance, the determination of the most advantageous mode of insulating the iron of armatures to avoid Foucault currents, in which case it is the current which must be avoided, not the generation of the difference of potential, for that cannot possibly be avoided except by an absence of all material, or by keeping the iron fixed in one position.

With a magnetic field of known strength, and with a given speed and direction of motion of the inductor, a certain definite electromotive force is developed, which may be theoretically calculated. But it is evident that with this electromotive force any desired current may be generated, according to the resistance of the circuit through which this electrical pressure equalizes itself, showing that the current is directly dependent only on the electromotive force and resistance, and not on the magnet nor the speed.

CHAPTER III.

Magnetism and Electro-Magnetic Induction.

AMONG the different units and expressions used in representing and measuring magnetism and magnetic forces, and the laws by which these are governed, the most important are the following.

Lines of force are units in terms of which magnetism may be expressed and measured. A magnetic field which is nothing more than a space in which magnetism exists, may be said to contain lines of force. The direction and polarity of these, indicate the direction and polarity of the magnetic force; their total number is a measure of the amount of magnetism; while the number per square inch of area, measured perpendicularly to their direction, is a measure of the intensity of magnetism at that point.

This conception of magnetic force may perhaps be better understood if compared to the force of gravity similarly represented. Imagine a heavy body suspended in the air, and suppose every cubic inch of the material of which the body is composed, to weigh one pound. If an imaginary line be drawn to the earth from the centre of gravity of each cubic inch of the suspended body, the direction of these lines would represent the direction of the force of gravity; their total number would represent the total force in pounds, while their density, or the number of lines per square inch area (measured perpendicularly to their direction) would represent the intensity of the force at that point. In precisely the same way as these lines represent the direction, amount, and intensity of the force of gravity in that body, so do the lines of magnetic force represent the direction, amount, and intensity of magnetism, except that in the latter there is no constant direction of action such as the downward force of gravity, lines of force

acting in both directions as if trying to shorten their circuit, like a stretched rubber ring. The lines do not exist as such, any more than they do in the analogy of the force of gravity, it is merely a convenient way of representing magnetism in order to facilitate the conception and computation of problems.

The *amount or quantity of magnetism* is therefore expressed by the total number of lines of force. *Magnetic density, or intensity of magnetism* is expressed by the number of lines of force per square inch area measured perpendicularly to their direction. The *polarity* of a magnet or a magnetic field, is represented by the *direction* of the lines of force (indicated by arrow heads), as distinguished from their *position.* The *axis* of magnetization is a line parallel to the path of the lines of force.

A single line of force, or unit, is that amount of magnetism which passes through every square centimetre of cross section of a magnetic field whose intensity is unity. Such a magnetic field exists at the centre of curvature of an arc of a circle, whose radius is one centimetre, and whose length is also one centimetre, when a current of 10 ampères flows through this arc. Or, stated in the language of the practical electrician, it is the amount of magnetism which passes through an area of one square centimetre, at the centre of a coil of one turn, having a diameter of 10 centimetres, when a current of about eight ampères (accurately 7.9578) flows through the wire. The intensity of magnetization in the area enclosed by a circular coil is different in different parts, being least in the center and strongest nearest the circumference.

A uniform field, or field of uniform intensity, is one in which the number of lines of force per square centimeter is the same throughout the field. The best illustration of a uniform field is the magnetic field of the earth at any one place. The intensity of the earth's field in the direction of the "dip" is about .5, which means that through every square centimeter measured perpendicularly to the

direction of magnetization, ½ of a line of force passes, or in other words, through every two square centimetres one line of force passes.

The *direction* assumed for lines of force (generally indicated by arrows), as distinguished from their *position*, is, of course, arbitrary, as they have no such direction of

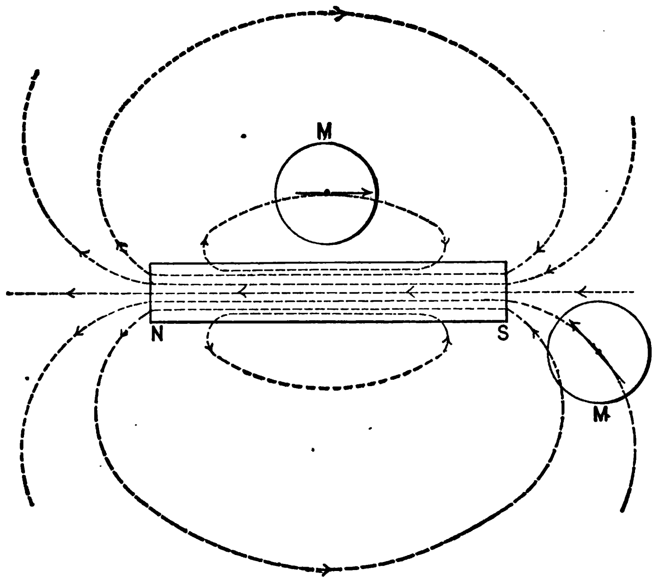


FIGURE 1.

action, as mentioned before, but in practice it is very convenient for defining terms and for stating laws, to concede them to have a certain direction, and it has become universal to consider them as emanating from the north pole of a magnet and entering the south pole, as shown in figure 1. Thus the direction of the lines of force in any magnetic field would be the direction in which a magnetic

needle M, figure 1, points, if made as usual, in the form of an arrow having the point at the north (north seeking) end.

An electric current is always surrounded by lines of force which encircle it, their density decreasing as their distance from the current increases, as shown in figure 2. Assuming that the lines of force have a direction as just described, then *if the current flows away from the observer, the line of force will pass around in the same direction*

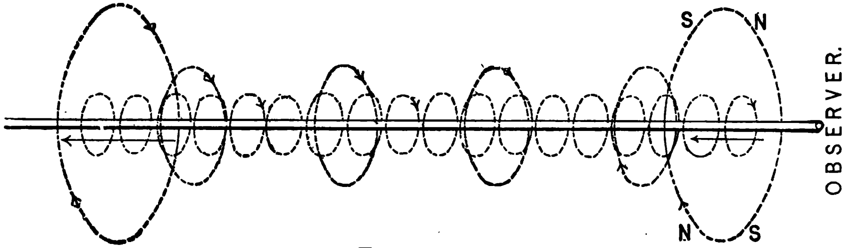


FIGURE 2.

as that of the hands of a watch, as will be seen in figure 2. In other words, below the wire the north pole will be to the left and the south pole to the right, while the reverse is the case above the wire.

From this the laws of the polarity of electro-magnets follow. In looking *at the face of the pole, if the current flows in the direction of the hands of a watch, it will be a south pole, and if in the other direction it will be a north pole,* as illustrated in figure 3, which shows some of the lines of force encircling the wires of the coil and condensing in the poles of the magnet. This rule is easily remembered, as it is the same direction as that of the rotation of the earth in looking at its geographic north and south poles from points in space.

Lines of force which have the same direction repel each other, while if they have opposite directions they attract each other. This explains why like currents of electricity attract, and unlike repel each other, as will be seen in fig-

ure 4, in which two like and two unlike currents are shown with some of their lines of force encircling them; in the first two the neighboring lines of force are unlike, in the last two they are like.

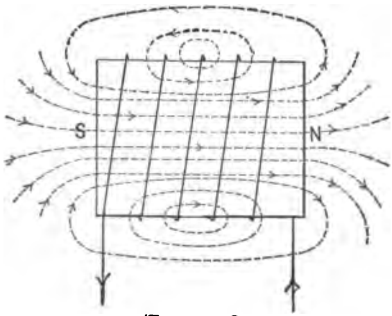


FIGURE 3.

The following properties of lines of force and of magnets, will frequently be found useful in designing machine magnets. Every line of force makes a complete closed circuit, that is, it emanates from a north pole, passes through the field around to the south pole and returns to the north pole again through the magnet. From this it follows that the number of lines of force is the same in all the cross sections of their complete circuit, and therefore the intensity of a field is inversely proportional to its cross section if it is uniform, showing that the most intense field is in the iron of the magnet where it cannot be utilized. It also follows from this that around a single pole the intensity of the field (number of lines of force per unit area) diminishes as the square of the distance to the pole.

Magnetic materials readily conduct and, therefore, also condense in them, lines of force[2] while non-magnetic materials offer great resistance to them.

2. It is claimed by some that iron merely conducts and condenses magnetism, but has no inherent magnetism of its own. It is very doubtful whether this last statement is correct.

In applying these properties of lines of force to dynamos, it follows that all the parts of their circuit should offer the least possible resistance to them. For instance in the Weston type of frame, with four coils, the cross section of the end pieces should be at least equal to that of the core of a magnet; that of the pole pieces measured perpendicularly to the direction of the lines of force, should be at least double that of a core; the iron of the armature, measured horizontally should have at least twice the cross section of a core, if it were made of the same material; and as the space between the armature and pole pieces offers the greatest resistance, it should be made as short as possible in the

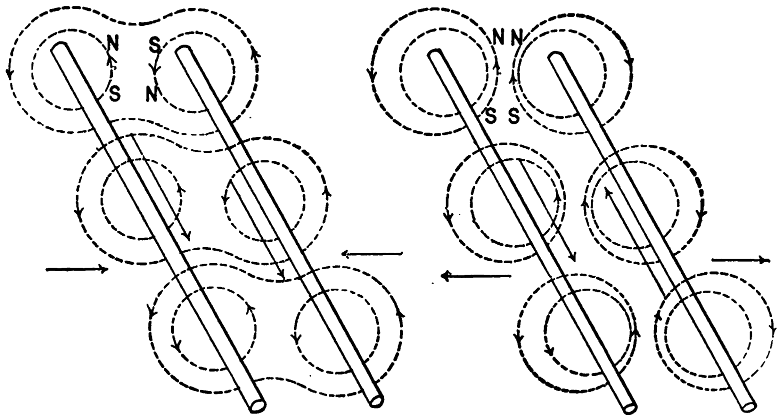


FIGURE 4.

direction of the lines of force and have as large a cross section perpendicular to this direction, as other considerations will permit. The average thickness of this space may be reduced by projecting iron lugs between the wires (like in

a Pacinotti ring armature as distinguished from a Gramme), which S. P. Thompson has shown increases the effect.[3]

In regard to the magnetic properties of wrought and cast-iron, a certain authority states that for the same coil and current the magnetism of a wrought iron core is 30 per cent. greater than that of a cast iron one. From this it follows that if the cost of the wire and iron of a 30 per cent. larger cast iron magnet is less than that of the smaller wrought iron one of equal strength, then the former should be used, notwithstanding its increased size and its poorer magnetic properties. The relative cost of wrought iron and cast iron magnets depends evidently on the style of the frame of the machine. S. P. Thompson states that a cast iron magnet has only 60 per cent. of the effect of a wrought iron one of the same size. He also states that the permeability of iron to magnetic lines of force is from 40 to 20,000 times that of the air, from which it would follow that the cross section of an air space in the circuit of the lines of force, measured perpendicularly to them, would have to be 40 to 20,000 times that of the iron to offer the same relative magnetic resistance.

Lines of force can never intersect each other; when a number act at the same point, in different directions (as in a galvanometer in the earth's field, or in the combined field of an armature and its field magnets), their total action will be represented in intensity and direction by their single resultants. If such a resultant is allowed to act, as in the case of a magnetic needle containing fixed lines of force in it, suspended so as to be free to move, then the effect will be to move the needle until this resultant passes through the centre at which the needle is suspended. This illustrates the law that lines of force strive to arrange themselves parallel to one another.

Lines of force act as though they were elastic, tending

3. *Dynamo Electric Machinery*, 1st edition, p. 66-69.

to make their complete circuit as short as possible, and exerting a lateral repelling force upon one another, thus tending to equalize the magnetic density in a homogeneous medium. The resultant of these two actions at different points determines their position and density, as illustrated in the field around a bar magnet by the well-known experiment of throwing iron filings on a glass plate covering the magnet.

Some of the general laws of electro-magnetic induction are as follows:

The electromotive force generated by moving a conductor in a magnetic field, is proportional to the number of lines of force cut per second or to the rate of cutting lines of force. It therefore increases with the speed of the moving wire and with the number of lines of force cut, but not with the size of the field passed through per second without increasing at the same time the total number of lines of force. It follows from this that the greatest effect is produced by cutting them perpendicularly, for then the number passed through in the same distance of motion is greatest. It also follows that moving the conductor in the direction of the lines of force generates no potential, as in that case none are cut.

By definition, one volt electromotive force is generated for every 100,000,000 lines of force cut per second, or in other words, the electromotive force in volts generated in the inductor is equal to the total number of lines of force cut, divided by 100,000,000 and by the time in seconds in which it passes through them.

The direction of the motion in motors, or the direction of the current in generators, may be determined by the following "rules of thumb," which are more practical and often less awkward in their application than Ampère's well-known rule of "swimming in the current."

In the conditions of Oersted's experiment the letters of the word *NOSE* give the initial letters of the principal words of the rule "If the current passes from the *N*orth

pole *O*ver the needle to the *S*outh, the deflection of the north end will be toward the *E*ast." Similarly the word *SNOW* is the key to the rule "If the current flows from the *S*outh to the *N*orth *O*ver the needle, the north end will be deflected toward the *W*est."

In applying these rules to generators it need only be remembered that if the inductor be moved near the magnet, the current induced will be in the opposite direction to that which would produce this same motion.

A still better practical rule, and one which is very easily remembered is illustrated in figure 5. If a north pole of a magnet be grasped in the right hand, as illustrated, and

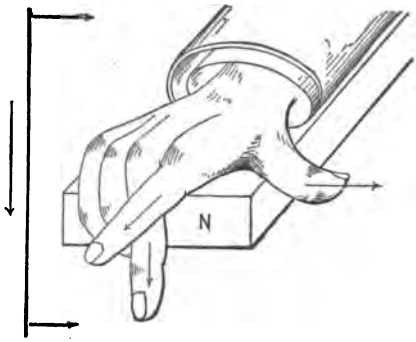


FIGURE 5

the three fingers of the hand be held in the position shown, then the fore finger will point in the direction of the lines of force, which are assumed to emanate from a north pole; and if the thumb points in the direction of motion of the inductor or moving wire, that is, perpendicular to the lines of force, the third finger will then point in the direction in which the current will tend to flow under these conditions. In other words, if a wire be moved past a north pole in the direction in which the thumb points, the induced current

will tend to flow in the direction in which the third finger points. This is called Fleming's rule. In this as well as in the other rules, it is evident that if one of the conditions be reversed, then the current, or the motion, as the case may be, will be in the opposite direction, while if two conditions be reversed, the current or the motion will be in the same direction. For instance, if a north pole be grasped similarly in the left hand it will give the conditions of a motor or of Oersted's experiment, the thumb in that case pointing in the direction of the motion which the wire (not the magnet) will have if the current in it flows in the direction as indicated by the third finger.

In connection with the above rules it must be remembered, as before pointed out, that it is the electromotive force and not the current which is induced, and that, therefore, the electric polarity of such a wire in which induction takes place, is the *reverse* of what it would have to be to cause that current to flow through the conductor. In other words, as the positive pole of the inductor is the one *out of* which the current tends to flow, it follows that the current in the inductor itself flows from its negative to its positive pole, just as in a battery in which the current in the liquid flows from the negative (zinc pole) to the positive (copper or carbon) pole, and not from the positive to the negative as in the external circuit.

It follows from the above laws that with a magnetic field of a certain strength, and a moving inductor having a given speed and position in the field, a certain definite electromotive force will be generated which is quite independent of the resistance of the circuit. From Ohm's law it follows that any desired current can be generated with a certain electromotive force as it depends only on the resistance. Therefore, it is evident that any desired current can be generated with a given magnet and a given speed of motion and position of the inductor, or in other words the current is not directly dependent in either the magnet or the speed, but is the quotient of the electromotive force

divided by the total resistance, the latter quantity being in most cases a variable one.

In one sense, however, the electromotive force in an electric machine as distinguished from batteries, is to a certain extent dependent indirectly on the current, for when it flows in the inductor it tends in all cases to oppose or weaken the magnet, and therefore indirectly affects the electromotive force. In other words the counter-magnetism of the armature of a machine tends to weaken the field, hence the practical rule : Make the magnetism of the field as strong as possible, and the counter-magnetism of the armature as weak as possible, which is done by making the number of windings on the armature as small as possible.

It may be well to call attention here to a distinction between the terms "electromotive force" and "difference of potential," which it is very desirable to adhere to as strictly in English as is done in the French and German languages, as it often aids greatly in clearness of statement. Difference of potential, is, as the name implies, the difference of the electrical potential at any two points of a circuit, and may therefore be applied to that at the poles of a machine, battery, or lamp, or at the ends of leads, or in general to any two points in a circuit. The term "electromotive force," however, applies only to the maximum difference of potential which exists in the circuit, or in other words, the total generated difference of potential. It applies, therefore, only to the generators of differences of potential, such as machines or batteries and to counter or opposing differences of potential developed in motors, arc lamps, or in the charging of secondary batteries. The available difference of potential at the poles of a generator is therefore its electromotive force, less that which is absorbed by the internal resistance of the generator, and which according to Ohm's law is dependent on the current, while the electromotive force is not dependent on the current (except indirectly as mentioned above, as in the case of machines or in polarizing batteries). In generators

the two are equal when measured on open circuit, with an electrometer or any other instrument in which no current needs to flow.

CHAPTER IV.

Generation of Electromotive Force in Dynamos.

THE primary object in a dynamo electric machine is, as was explained in chapter ii, to generate an electromotive force or electrical pressure; the resulting current, which depends on the resistance in the whole circuit through which this electromotive force equalizes itself, is, in general, of secondary importance in the construction of machines. Just as in the case of a number of batteries for strong currents, the first consideration is to develop the required electromotive force, which depends only on the chemical constituents and the number of cells; the current which they are required to give is of secondary importance, and affects only the size of the plates in permitting this current to pass through the battery itself without too much loss. If a machine has been constructed to give a certain electromotive force, the greatest current which it will be able to maintain depends, in general, only on the thickness of the wire in the machine through which this current has to pass. The current, therefore, affects the construction only in the detailed dimensions of the machine, which will be discussed under the details of construction, the present chapter being limited to the methods of generating the electromotive force.

In a dynamo electric machine the electromotive force is generated, as was shown in chapter ii, by moving a wire near a magnet, or through a magnetic field, and depends for its value on the amount of magnetism passed through by the wire per second, or, as it is generally stated, on the number of lines of force cut per second, or on the *rate* of cutting lines of force. If the number of lines of force could be determined, the electromotive force in volts could

be calculated, one volt being generated for every 100,000,000 lines of force cut per second.

In machines this electromotive force depends on the speed with which the wire passes through the field, and on the amount of magnetism passed through by that wire; it may therefore be increased by increasing either of these. The amount of magnetism passed through by the wire may be increased by one or more of the following different ways:

First. By increasing the intensity of the magnetic field, that is, the magnetic density or number of lines of force per square inch.

Second. By increasing the size of the field of the same intensity as before, or in other words, by increasing the total number of lines of force without increasing their density.

Third. By increasing the number of armature windings, or in other words, by making successive parts of the same continuous wire pass simultaneously through the same field, by winding it in the form of a coil, and moving this coil through the field, thus generating an electromotive force in each single turn or winding of the coil. As these turns or parts of turns are, from the nature of the continuous winding of a coil, all connected in series with one another, it follows that all the small electromotive forces which are generated in each of the turns, are also connected in series with one another, thus summing all the small potentials into one large one.

Fourth. By passing the same wire in opposite directions through two fields of opposite polarities; for instance, by causing a coil of one turn to revolve between a north and a south pole, as, for instance, the coil 6-5-4-3 in figure 7, in which the motions of the parts 6-5 and 4-3 are in opposite directions, and the magnetic poles near which they are have opposite polarity. From the laws of induction, therefore, the currents in these two parts will tend to flow in opposite directions, which, as will be seen by following the

current, is equivalent to inducing a current in the same direction around the coil, or in other words, the two electromotive forces generated in the two parts, 6-5 and 4-3, will be added, giving double that induced by each pole.

The electromotive force of a machine may therefore be made any desired number of volts, by simply increasing any one or all of the following: the speed, the intensity of the magnetism, the size of the field passed through in the same time, the number of times that different parts of the same wire are wound so as to pass simultaneously through the same field, that is, the number of armature windings, and lastly, the number of fields passed through by the same wire. Any desired potential, however large, could be generated at even a very low speed, if it were possible to increase the magnetism and the number of armature windings to the proper amount. The weak magnetic field of the earth might be used to generate a very high electromotive force if it were possible to increase the speed of an armature or the number of its windings, or both, to the required amounts. It is evident, however, that such machines, although giving the required electromotive force, would not be practical, on account of their abnormal proportions. As there are so many different combinations of the methods just given, by means of which the same electromotive force may be generated, and as some of these will be more practical than others, or less expensive in their application, it follows that in most cases there will be one combination which is the cheapest to construct and the most efficient under the given circumstances, and this proportion of parts it is the object of the electrical engineer to determine.

The following remarks on the different methods of increasing the electromotive force, besides those already given in connection with magnetism, and those which will follow in discussing the details of construction of magnets and armatures, may be of assistance in determining the best combination of parts under different circumstances.

The speed of the wire may be increased by increasing either the number of revolutions or the diameter of the armature, that is, the distance of the wire from the axis of rotation. The general rule in regard to speed is to make both the number of revolutions and the diameter as large as other considerations will permit, for it is evident from what was said above, that the higher the speed the less the magnetism or the number of windings on the armature, and, therefore, the smaller the machine for generating the same electrical energy. The limiting conditions for the speed are purely mechanical, and will be discussed under details of construction.

The intensity of an electro-magnet, that is, the number of lines of force per square inch, may be increased to almost any amount; but, as iron becomes saturated, the economical limit to the intensity is soon reached. If a current is passed through a solenoid, that is, an electro-magnet without an iron core, it will be found that the magnetism of that coil increases slowly in proportion to the current, and it may be increased to any desired amount by simply increasing the current. If an iron core be inserted, and the same series of experiments made, it will be found that the amount of magnetism for the same current is very much greater than it was before, and that it also increases approximately proportionately to the current. But a limit is soon reached when the iron ceases to add to the increasing amount of magnetism, and it is then said to be saturated. After this point is reached the magnetism will still increase with the current, but only slowly, as in the first case of a coil without a core. This point of saturation is the degree of magnetization at which all machines should be used in practice, in order to give the greatest amount of magnetism for the smallest expenditure of iron, wire and current. If a less degree of magnetization is used the magnets are unnecessarily large, and the amount of copper wire therefore unnecessarily great. If the iron is over-saturated, then the amount of magnetism

developed by a certain amount of current is not as great as it might be, and therefore the proportions are not the most economical.

From this the general rules follow: Diminish the amount of iron so that the magnets may be just at the point of saturation for the required amount of magnetism. Also, proportion the cross section of the iron at different parts of the magnetic circuit, so that it may all be saturated at once. This will be further discussed under the subject of magnets.

The size of the magnets should evidently be as small as the required amount of magnetism and the saturation limit will permit, for reasons just given. This must not be confounded with the practical rule which will be explained hereafter, namely, that the amount of magnetism should be as great as practicable, which simply means that the *amount* of magnetism, as distinguished from the number of armature windings, should be made great, but that for this given amount of magnetism the size of the magnet should not be larger than the saturation limit will necessitate, as the machine will otherwise become unnecessarily large and bulky, and the amount of wire on it will be greater than it need be.

The magnets should be of the construction best adapted to collect and concentrate all the lines of force generated by the magnet coils, into the space through which the moving wire passes, as it is evident that only those lines of force which pass through this space will be rendered useful. All the others are wasted. This subject of size and shape of magnets will be further discussed under the subject of details of construction of magnets.

The third method of increasing the electromotive force, namely, by causing the same continuous wire to pass repeatedly through the same field, is best illustrated by the ordinary well-known Gramme armature. An iron ring, figure 6, is wound spirally with a continuous wire, the end of which is connected to the beginning, so as to make

it an endless coil closed in itself. This armature is then revolved between a north and south pole, as shown in the figure. If the direction of rotation and the polarity of the magnet poles are as shown, then the currents induced in all the portions of the wire, which are between the iron ring

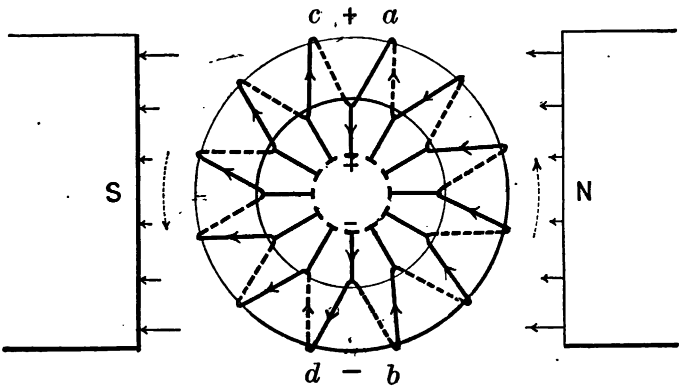


FIGURE 6.

and the north pole, will tend to flow toward the observer, according to the rules of induction, while in the wires under the influence of the south pole, the currents will tend to flow away from the observer. From the nature of the winding, it will be noticed by following the wire around the core, that the active portions between the iron ring and the pole piece, are connected in series with one another by those portions of the wire which lie in the inside of the ring, or, in other words, the same wire is wound so that it returns through the inside of the ring, and passes repeatedly through the same field. The small electromotive forces induced in each of these active parts as they pass simultaneously through the field, are therefore added in

series, and at the two points *a* and *b* of that wire, where it enters and leaves the north magnetic field, the total electromotive force will be the sum of all the small electromotive forces induced in each turn. The potential which it is possible, in practice, to generate in a single wire in passing through the field once, is exceedingly small, being in the more common machines about a volt, and in some exceptional (and impractical) cases a few volts. It is therefore, necessary, in all machines to cause successive parts of the same wire to pass simultaneously through the same field, in order not to have the magnets too large and costly, nor the speed too great for safe running; in other words, the armature must contain numerous windings.

As the small potentials are, from the nature of the continuous winding, all connected in series, the well-known law becomes evident, namely, that the electromotive force of such an armature is approximately proportional to the number of turns or windings of the wire around the core. Or in other words, to increase the electromotive force it is only necessary to increase the number of windings in the same proportion, provided this can be done without changing any other parts on which the electromotive force depends. This electromotive force must not be confounded with the available difference of potential at the poles of the machine when running, as mentioned in chapter iii, for the latter will not increase in proportion to the windings, as it depends on the current which is flowing and on the size of the wire; it will in all cases be less than the electromotive force.

Referring again to figure 6, we notice that in that portion *a b* of the continuous wire around the core which is under the influence of the north pole piece, the summing up of the small potentials causes the total to act at *a* and *b*, making a positive pole at *a* and a negative at *b*. In examining that portion of the same continuous wire which is in the other field, the same is the case, with this difference only, that the direction of the inducted current will be the

reverse, thereby causing a positive pole to be developed at *c* and a negative at *d*, which can readily be proved by applying the rules of induction given in chapter iii. The two currents, therefore, oppose each other at the two points of the wire which are not under the influence of the magnetic fields. These are the points at which the current must be led off by the usual method of applying brushes at these places, as they remain fixed in position under the same circumstances, while the wire moves. This might be done by making the wire bare at those parts which have to come in contact with the brushes, and then applying the brushes directly to the outside of the armature. But as this is not practicable, for numerous reasons, the continuous wire is connected at regular and frequent intervals to the thick, insulated bars of the collector, or so-called commutator, on which the brushes are made to bear.

The function of this collector in a Gramme ring armature, is, therefore, merely a mechanical one, to prevent the wearing off of the wires, and to present a broad contact for the brushes. It is therefore not really a "commutator," its function not being electrical, as the brushes might just as well be applied to the outside of the armature directly on the wires if they are bare, were it not for the mechanical objections.

It is evident from the figure, that in this form of winding, the two halves of the continuous winding on the armature are necessarily connected in multiple arc, and therefore each half supplies the same electromotive force, but only half the current of the machine.

From the above remarks the following practical rules will be readily understood. As the two halves of the continuous wire are from the nature of the winding, connected in multiple arc, it is very important that the electromotive forces of the two halves should be equal, for if they are not, the difference between the two will, under certain circumstances, cause a reverse current to circulate in the armature wire, and as this current does not appear in the

external circuit, it is lost energy which might easily have been saved. The brushes should, therefore, be directly opposite to each other, and the magnetic fields should be perfectly balanced, that is, both fields should contain an equal number of lines of force.

As the two halves of the continuous wire are in multiple arc, it follows that the real resistance of the whole armature from brush to brush, is one-half the resistance of one-half of the wire, which is evidently equivalent to one-quarter of the resistance of the whole wire. As the whole current of the machine divides into two parts in the armature, the wire need be calculated for only half the current of the machine. The two halves being in multiple arc, the total electromotive force is evidently only half that which the same amount of wire, windings, speed and field, could produce. By some writers this is considered to be a grave fault of that form of armature; a little thought will, however, show that it is not such a serious fault, as the current thereby is twice as great as the same size wire could stand alone, and therefore the electrical energy developed, or the current multiplied by the electromotive force, is the same. If the two halves could be connected in series, the wire would evidently have to be about twice as large in cross section, and therefore the whole machine would become larger. The only practical loss due to this so-called fault, is, that slightly more space is occupied by the insulation on two thin wires in multiple arc, than would be required for one thicker wire. A device has been patented for connecting the two halves of a Gramme ring armature in series, but as the small advantage gained is obtained at the cost of simplicity, it is no improvement on the old form of Gramme ring.

Referring again to figure 6, it will be seen that in order to permit the wire to be wound so that successive portions pass simultaneously through the same field, a portion of every winding must return from one end of the armature to the other in a space in which no induction takes place,

that is in the space enclosed by the iron ring. As the lines of force which enter the iron of the ring are led through the core to the opposite field, it is evident that none will pass through the space enclosed by the ring, which has been repeatedly demonstrated with iron filings. The wire in the inside of the ring is therefore inactive, and may be considered dead resistance, because there is no electromotive force induced in it. It serves the purpose merely of connecting the two ends of the active portions which pass through the fields. For the same reason the wires at the ends of the ring are also dead, from which it follows that in many of the Gramme ring armatures, the dead wire forms from 60 to 70 per cent. of the whole armature resistance. According to the old theory of induction, this wire is not dead, and the question is, therefore, still a disputed one ; we believe, however, that the best authorities agree in saying that it is dead. A very simple experiment could readily be made to settle this important question.[1]

To overcome this alleged fault, the ingenious method was devised, of making the return wire of each winding pass through the opposite field, instead of through the inside of the ring, thus rendering it active in generating electromotive force. This, we termed above, the fourth method of increasing the electromotive force. Instead of making the iron in the form of a ring, it may then be made a solid cylinder, around the outside of which the wire is wound. It then becomes the well-known cylinder armature shown in figure 7. In this case the continuous wire, as before, passes repeatedly through the same field, but instead of being partially in a space in which there is no magnetism, half of it lies on the other side of the armature, in the other field, in which induction also takes place. In applying the rules of induction it will be seen that the current is induced in opposite directions in the same wire, in the two fields, but upon following these two directions along the same wire, it will be seen that they are really the same direction with reference to the continuous wire

[1] See Appendix II.

itself, and that, therefore, the two electromotive forces induced in the same wire in passing through two opposite fields, are added in series. This will be seen in figure 7, by following the continuous wire around the armature, starting at 1, and thence in regular order to 8. From 9 to 16 the same will be found to be the case, only that the current in this half is opposite to that in the first half, and therefore precisely similar in this respect to the two halves of the wire in the Gramme ring. All that was said about the latter, as regards the two halves being connected in multiple arc, also applies to cylinder armatures. The only wire which can be termed dead resistance in the cylinder

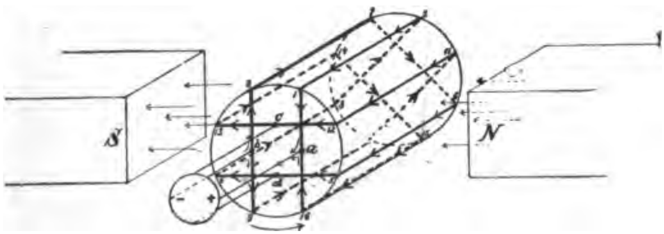


FIGURE 7.

armature, is that at its ends. By making the armature long in comparison to its diameter, this dead wire may be reduced to a small proportion of the whole. In a recent invention even this part of the armature wire has been rendered active.

The winding of the cylinder armature, which is often represented as being very complicated, is in general very simple. It may be considered to be an ordinary Gramme ring winding, in which the wire, instead of being wound alternately on the outside and inside of the ring, is wound on opposite sides of the core, in which case, the iron ring may be replaced by a solid cylinder, as there is no longer

any object in having the hollow space in the inside. The cylinder winding may also be said to be similar to the winding of a ball of twine, the wire being wound around the outside while the cylinder is being turned around slowly on its axis. In this case, as well as in the Gramme ring, the end of the wire after completing the winding, is connected to the beginning.

These two types of armature winding are given here merely as illustrations of methods for increasing the electromotive force in machines, by induction in successive parts of the same wire simultaneously, in the same magnetic field or pair of fields. They will be further discussed under the head of details of construction.

CHAPTER V.

Armatures.

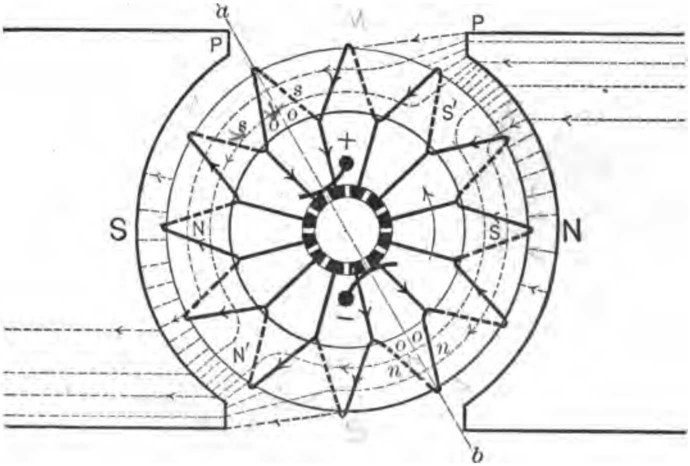
THE foregoing chapter having completed the short review of the general and leading principles involved in the generation of electrical energy by machines, the remaining chapters will be devoted to a discussion of the practical application of those principles to the construction of machines, together with practical rules and hints in regard to the proportioning of parts, both of armatures and of the field magnets. As almost all of the machines built in this country use either the Gramme or cylinder armatures, or variations of them, such as the Thomson-Houston or Brush, the discussion on armatures will be limited to these general types. Both of these forms being very similar in many respects, and the first being the simplest in form, the first part of the present chapter will be limited to the Gramme type; the subject of cylinder armatures will be confined merely to the differences between it and the Gramme.

In order to appreciate more fully the reasons for many of the practical rules for constructing armatures, let us examine in detail what takes place in a Gramme armature while running. In figure 8 is shown a diagrammatic representation of a simple Gramme armature with its collector, brushes and pole pieces, the directions of the currents and lines of force being represented by arrows, as they would be while the machine is running in the direction indicated, the polarity of the pole pieces being as represented.

The direction of the currents may be determined by the practical rule given in chapter iii. By grasping the north pole piece in the right hand, the middle finger, which points down, will indicate the direction of the current

if the wires between the armature core and the north pole piece were moving in the direction in which the thumb points, which in this case would be like the hands of a watch. As it turns in the opposite direction, however, the currents will also be in the opposite direction, which in this case will be from below up, thus giving the direction around the end of the armature as indicated. A similar application of the rule will show the direction of

Fig. 8



the currents at the south pole piece to be as indicated there, namely opposite to those at the north pole in the cylindrical portion of the armature, but in the same direction at the end of the armature, as will be seen in the figure.

From this the practical rule of thumb follows, for determining the direction of the currents in all types of Gramme as well as cylinder armatures, viz.: in looking at

the commutator end of the armature, *if the rotation is opposite to that of the hands of a watch, the currents at that end will have the same direction as the lines of force,* namely from the north to the south pole pieces. In following one of these currents to the brushes their polarity may be readily determined. This polarity of the brushes will evidently be different, depending on whether the general direction of the windings of the armature is a right hand or a left hand spiral, which can readily be determined by following a wire from one commutator strip to the next. If a correct drawing has been made of a machine, on which the polarity of the pole pieces, the direction of rotation, and the general direction of the spiral winding in the armature, are indicated, the polarity of the brushes and the binding posts, can evidently be determined before the machine is built, provided the machine is constructed as designed.

All the small electromotive forces induced in each of the windings of the wire around the armature core, will, from the nature of the continuous winding, be added in series, and therefore at the brushes the total electromotive force will be the sum of all the smaller ones on one-half of the armature, as explained in the last chapter. Supposing the electromotive force induced in each winding to be the same, the practical rule follows that the electromotive force of a machine is proportional to the number of windings on the armature; and it is equal to that induced in one winding multiplied by the total number of windings divided by two, as the two-halves of the armature windings are in multiple arc.

The pole pieces will induce a north and a south pole in those parts of the iron core of the armature directly adjoining them, as shown at the letters S and N on the core. If this were the only magnetization of the core the lines of force would take the shortest direction through the armature core, and the line of the brushes *a b*, or diameter of commutation, as it is called, would be perpendicular to

the magnetic axis of the pole pieces. In examining the magnetic effect of the currents in the armature wire, it will be seen that these currents also magnetize the core, in each half of which they tend to make two opposite poles, thus making a separate magnet of each half of the core, with north poles at *nn* and south poles at *ss*, as will be seen if the core is imagined to be cut into two parts through the line of the brushes *a b*, and the magnetic polarity determined at each end. These two independent magnetizations, one by the pole pieces and the other by the armature current, will tend to oppose each other to a certain extent, and will produce resultant poles at N′ S′. These will be the real effective poles in the induction and the lines of force will, therefore, be crowded to one corner of each pole piece, as shown in dotted lines, some of which are shown as they pass through the armature core. As the line of the brushes, *a b* (that is, the line through the two points where the currents induced in the two halves of the armature, meet), will be perpendicular, or nearly so, to this line of magnetization, it follows that the brushes will have to be shifted in the direction of rotation.

This shifting of the brushes is often erroneously attributed entirely to the so-called magnetic lag, which is the tendency of the iron core to retard its magnetization when entering the field, and to retard its demagnetization when leaving it. Although this is the case to a slight extent, it is, in a soft iron, laminated armature, very small as compared to the transverse magnetization by the armature current. It is very easy to determine how much of this displacement of the brushes is due to the magnetic lag, by finding the position of the brushes at which the greatest potential exists when the machine is running on open circuit, that is, without a current in the armature, in which case the magnets must be excited by another machine. This amount of displacement is then evidently due entirely to the magnetic lag, provided the armature is perfectly balanced electrically.

The shifting of the line of the brushes, when the armature is generating current, will be greater in proportion to the magnetization due to the armature coils, that is, in proportion to the number of windings on the armature; as its effect is very objectionable, because it practically makes the effective pole pieces narrow, causes bad sparking, etc., the important rule becomes evident, viz.: make the number of windings on the armature as small as possible, and therefore the other two factors on which the electromotive force depends, namely the speed and the field, should be made correspondingly great. There are, also, other reasons for this same important rule, which will be mentioned below. It is one of the most important rules in the construction of a well proportioned machine. In several cases in the writer's experience the capacity of a machine, in lamps, was doubled without any increase of size of the frame, by a proper application of this rule.

If one of the brushes were to leave a commutator strip before it touches the next, the circuit would be momentarily broken at that instant, which would result in forming a succession of small arcs. This is generally termed sparking, and is very injurious, as it burns off the brushes and the commutator bars. It is, therefore, absolutely essential that a brush should bridge over the insulation between two commutator bars and touch one bar before it leaves the other, as shown in figure 8.

From the nature of an armature winding, two neighboring commutator strips represent the two ends of one of the coils of the armature, and it therefore follows that while a brush touches two strips, that coil which terminates at those two strips, is short circuited through the brushes, as shown in the two coils marked *o o*. This current represents a certain amount of loss, as it does not appear in the external circuit. When the brush leaves a commutator strip, after having short circuited this coil, this local current is broken at the terminal of the brush, and therefore causes sparking. This is, perhaps, one of the chief among

the many causes of sparking, and should therefore not be overlooked. As this short circuiting cannot be avoided in the ordinary form of commutator, the only thing that can be done is to make the current in that coil as small as possible. It may be argued that the induced electromotive force in this coil is always small, but it must also be remembered that it is short circuited by a very low resistance and that the current may therefore be very great. For instance, if the induced electromotive force in that coil be only .1 volt and the resistance of that one coil .001 ohm, the local current would evidently be 100 ampères by Ohm's law, and when a current of 100 ampères is suddenly broken a spark will be produced, especially as the current flows through a coil which has self induction, the action of which is to tend to prolong the duration of the spark or arc, by suddenly increasing its potential.

The only way to reduce this objectionable current is to make the induction in that coil as small as possible and to decrease its self induction. The coil should, therefore, always lie near the neutral point in the field, and should be in the weakest part of it; it should, moreover, move in the direction of the lines of force so that there is little or no induction in it.

The ends of the opposite pole pieces, P P, nearest each other should, therefore, be as far apart as practicable, so that as few lines of force as possible pass directly from one to the other through these two short circuited coils. A good rule is to make this distance, P P, at least eight times the distance between the iron of the pole pieces and the iron armature core. It should even be more if practicable, but not less. From this it also follows that the distance from the pole piece to the armature core, or in other words the depth of the windings on the armature, should be as small as practicable. To keep the short circuited coil in the weakest part of the field the diameter of commutator, or line of brushes, should be shifted as little as possible from the position normal to the line joining the pole pieces,

in the case of a Gramme armature. This is another reason for making the armature windings as few as possible, as stated above. The field should be balanced, that is, it should be symmetrical both magnetically and in the outline of the iron parts, in order that not only the brushes but also the short circuited coils should be exactly diametrically opposite. The brushes should not short circuit more than one coil, and should therefore not touch more than two strips at any time; neither should there be two brushes on each side, the distance between which is greater than the width of a commutator strip, as they would then short circuit more than one coil. Finally, to decrease the self induction of these short circuited coils, the number of windings per coil should be as small as possible and consequently the important rule that the number of coils or number of commutator strips should be as great as possible to diminish the number of windings per coil. As the self induction increases with the square of the number of windings in the coil, halving this number by doubling the number of coils or commutator strips will diminish the self induction in the short circuited coil to one-fourth of what it was before.

As the direction in which the currents tend to be induced in all the coils of the armature depends only on the polarity of the pole pieces and the direction of rotation, it is independent of the position of the brushes. From this it will be seen that if the brushes are moved to different parts of the circumference of the commutator the direction in which the current will have to flow in some of the coils will be opposed to that induced in them, and therefore the electromotive force of these opposing coils will be subtracted from the rest and the difference will appear at the brushes. This is often made use of to regulate the electromotive force of a machine. It is similar to regulating the difference of potential of a set of accumulators, by connecting one or more so as to oppose the others. The difference in the amounts of energy at the

poles is therefore not wasted, but is stored up again in the few cells which oppose the others; or in the case of a dynamo the current in the opposing coils tends to make it a motor. This method of regulating is therefore in that sense not uneconomical, but it has the very serious objection that as the brushes are shifted to different parts of the commutator, the coils which are short circuited by them are no longer in a weak neutral field but have considerable electromotive force generated in them, and therefore the current circulating in them when short circuited by a brush will be very great, and the armature will therefore heat, waste energy, and spark badly at the commutator the more the brushes are moved from their proper position. Unless some device is used for blowing out these sparks, as in the Thomson-Houston machine, such regulation should not be used in well-built machines except within very small limits.

When two brushes are used on each side of the commutator, both leading to one terminal, the coils lying between them are necessarily short circuited by them, and if there is the slightest induction in these coils there will be a local current flowing through them, which heats the armature, wastes energy and causes bad sparking.

Another cause of sparking is the self induction of the coils in the armature. This is similar to inertia in mechanics, and is that quality of the coils by virtue of which they resist the starting or stopping of a current through them. It acts every time a brush makes, or breaks contact with the next commutator strip, as this starts or stops a current in the corresponding coil. As this self induction is proportional to the square of the number of windings in the coil, the same important rule follows that the number of windings on the armature should be as small as possible, and for a given number of such windings, each coil should have as few as possible by making the number of coils or commutator strips correspondingly great.

It will be seen from figure 8 that the wires of two

neighboring coils never have a greater difference of potential in them than that generated in one or two coils. For instance, if there were 64 coils and the machine gave 64 volts, it is evident that each coil generated on the average about two volts, as 32 coils are connected in series. Two volts, or at most four volts, is the greatest potential in any two neighboring wires. There is, therefore, no likelihood of the current "jumping" from one to the other, which is the reason why the Gramme armature is especially well adapted for high potentials. This is a characteristic and important difference between it and the cylinder armature, in which the whole difference of potential can exist between two neighboring wires, as will be explained later. In all armatures it is important to insulate, very carefully, the wires from the core, for if this insulation should be crushed or should rub through at one point, the whole electromotive force of the machine will act at another point to burst through the insulation and cause the current to "jump" through to the core, thus burning out the armature. This is the most frequent cause of armatures burning out; an armature should not be used in which any one point of the wire touches the iron core. The core should have all corners and edges rounded; it should have no sharp ridges, or burrs produced while turning it in the lathe, and above all there should be no loose parts which may rub against the wire, and no parts which can get loose when the armature expands on being heated.

As the two halves of the armature winding are in multiple arc, it is very necessary to have the electromotive forces induced in each half equal to each other. For suppose there was a difference of one volt, it is evident that when the machine is running on open circuit there will be a wasted local current circulating through the armature wire, which will be approximately equal to one volt divided by the resistance of the two halves of the armature wire in series. If this were .01 ohm, this local current circulating in the armature would be almost 100 ampères, the

self induction tending to reduce it somewhat. This local current becomes less as the current in the external circuit increases. It is, therefore, very important to have the same number of turns in all the armature coils, to have them all symmetrically situated with respect to the field and the axis, and to have a balanced field.

This is especially important in a cylindrical armature, which is often less symmetrical than the Gramme. If the two electromotive forces were not equal, the armature would be like two batteries having unequal electromotive forces and connected in multiple arc, in which case the stronger would evidently charge the weaker on open circuit.

In regard to the magnetism of the armature and the distribution of the iron, the following are among the most important rules to be guided by. As the space between the pole piece and the core of the armature is composed of the non-magnetic materials, air and copper, it offers the greatest resistance which the lines of force have to pass through, in their magnetic circuit. This space should therefore be as thin as possible measured radially to the armature or in the direction of the lines of force ; it should also have as large a surface as possible measured on the cylindrical surface of the armature, which is the same as the active surface of the armature. By reducing the thickness of this space by one-half, it does not follow as is sometimes supposed, that the magnetism will be four times as great, as the well-known rule that the magnetic intensity varies inversely, as the square of the distance does not apply to the distance between the two neighboring surfaces of two large magnets. Although the magnetism does not increase inversely as the square of this distance, yet it is increased very much by reducing this distance between the armature core and the pole pieces. It therefore follows from this also, that the number of windings in the armature should be made as small as possible to reduce this thickness ; also that the thickness of the copper wire

should not be greater than is necessary to carry the current without heating too much. The diameter of the armature core should be as large as practicable, and its length, or the length of the pole pieces, should be as great as practicable, in order to increase the area of this non-magnetic space.

Prof. S. P. Thompson has made some experiments[1] designed to show that by placing iron ridges or partitions between the armature coils extending from the iron core to near the pole pieces, the electromotive force will be considerably greater. As the number of windings and the speed in this experiment were the same in both cases, it follows that the magnetism must have been thereby increased. The iron projections or lugs as shown in his illustration were very large and massive, and it is therefore a question whether the increased effect was due to the increased amount of iron or to the different shape, as it is possible that his Gramme armature core was over saturated. It is also a question whether the electromotive force would not be increased by omitting these lugs and filling the space occupied by them with some additional windings on the armature. This could readily be proved by a simple experiment.

The lines of force pass through the cores of the magnets, the pole pieces, and thence through the armature core as shown in figure 8. The most economical cross section of these parts is, as explained before, that at which the iron is just saturated. Supposing that the field magnet cores have been so proportioned, the cross section of the armature core can then readily be calculated. For instance, if there are four magnets, as in the Weston type of frame, the iron ring of the Gramme armature should evidently have a cross section equal to that of one field magnet core; for as many lines of force pass through one half of the ring as through one field magnet core, as will be shown in discussing field magnets. This supposes the

1. Dynamo-Electric Machinery; pages 66-69.

quality of the iron to be the same in both. As the field magnets are generally cast iron, while the armature core is wrought iron, its cross section would need to be only about two-thirds as great. On the other hand, the armature core is not solid but is generally laminated or made of wire, so that if the outside cross section of the core when completed is taken, it should be made greater than $\frac{2}{3}$ by the amount of the non-magnetic space between the laminæ.

The so-called Foucault currents in an armature core are nothing more than currents which are induced according to the same laws, and in the same direction as the useful currents in the copper wire, only that they are induced in the iron where they cannot be used; for it is evident that induction will take place in any moving metallic parts of the armature which cut lines of force, whether these parts be copper conductors or masses of iron forming the magnetic core. It will be seen from this that the Foucault currents tend to flow in the core under the windings, in the same direction as the useful currents, that is, parallel to the axis, and in two opposite directions on the two sides. They are most intense in the outer portions of the core, as the speed and number of lines of force cut are greatest there. By omitting the core and winding a Gramme armature entirely of coils of iron wire, connecting them to the commutator as usual, the Foucault currents then become the useful currents and will be the only currents induced. In this case the iron wire coils act at the same time as a magnetic core, and as conductors of the current. As the resistance of iron wire is so high, this method does not appear to have been a success in practice. It is given here merely as an illustration of the nature of Foucault currents.

As with the useful currents, the Foucault currents are the result of an induced electromotive force equalizing itself through a certain resistance. To prevent these currents from being generated it is necessary either to prevent

the induction of the electromotive force, or to prevent the electromotive force from equalizing itself by making the resistance infinitely great. The former is impracticable, for the only way to prevent the induction of electromotive force in the core is either to keep the core fixed in position so as not to cut lines of force, or else to omit the core altogether or make it of wood or some other non-conductor. The only practical way, therefore, to avoid the generation of the currents is to make the resistance very great by laminating or otherwise dividing the iron core into a large number of small insulated parts. As the direction of these currents is the same as that in the copper wires, this lamination must be perpendicular to the copper wires, that is perpendicular to the axis. An armature core should therefore be made of discs, rings, or wires in planes perpendicular to the axis, and insulated from each other so as to prevent currents from flowing parallel to the axis or the copper conductors. The induction of small electromotive forces will nevertheless take place in each disc, but they will not be connected in series and cannot produce currents; they will therefore not consume energy, nor heat the core, as energy is electromotive force multiplied by current. The discs should be as thin as possible, for if they are too thick the unequal induced electromotive forces in different parts, which are moving at different speeds, will cause currents to circulate in each disc.

The cores should be made of the softest wrought iron, to diminish the amount of magnetic lag mentioned before. In well proportioned and well designed machines they should never be made of cast iron, even if it is cast massive, and then cut so as to be a substitute for laminæ. Cast iron has a lower saturation point than wrought iron, therefore cores of cast iron require a larger bulk of iron, than when made of wrought iron. This, at the same time, will increase the length and, therefore, the resistance of the copper wire, thereby decreasing the efficiency of the

machines. A core of a Gramme or cylinder armature should under no circumstances be solid iron.

If the laminæ are to be made of rolled wrought iron, it will generally be found that the iron sheets are coated with a thin layer of blue oxide. This is very hard and acts to retard the magnetization and demagnetization. This should be removed, which can readily be done by immersing the discs for a short time in dilute sulphuric or hydrochloric acid (about 1 to 10), after which they should be washed very thoroughly in water, and preferably immersed in a bath containing soda or potash, otherwise the acid will rust them badly after the armature is made.

In order to see whether this blue oxide retarded the demagnetization, the writer made the following experiment: Several discs were taken from the same lot; some of them were cleaned as described, while the others were left with the coating of blue oxide on them. They were fastened together and magnetized very strongly in one direction, all being magnetized to the same degree. After this they were examined for magnetism, and it was found that the clean ones had very little residual magnetism, while the others showed strong magnetic polarity.

CHAPTER V.

Armatures.—(Continued.)

IN chapter IV. it was stated that the wire in the inside of the ring was a dead resistance, as there is no induction in it. Numerous devices have been used to render it active, among which are the following:

The pole pieces have been made to embrace almost the entire surface of the ring, by shaping the ends so as to project into the inside of the ring, as shown in figure 9.

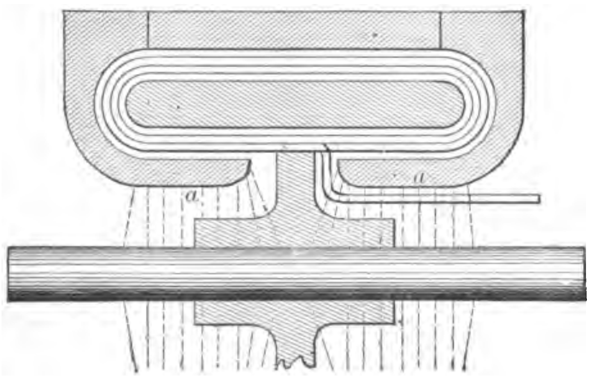


Fig. 9

This will increase the intensity of the lines of force somewhat, because it decreases the magnetic resistance of the circuit of the lines of force by increasing the active area of the two magnetic surfaces of the core and the pole pieces, between which the lines of force have to pass. For instance, if this surface is doubled by these

pole-piece extensions it is equivalent to reducing the thickness of this air space about one-half, and thereby reduces its resistance to one-half. If the surface of the pole pieces is not over-saturated without these extensions, then by adding them, thereby doubling its area, for instance, the magnetism of the field magnets may also be doubled, provided the rest of the iron of the magnets be increased so as not to be over-saturated. This will double the number of lines of force, and, therefore, also the electromotive force generated. This method of making the wire active is, however, not to be recommended, for by adding these extensions the construction is complicated very much. It will be seen from the figure that unless the armature is very large in diameter, many of the lines of force would pass directly from the points *a a* of one of the pole pieces through the iron shaft to the opposite pole piece, which would evidently be leakage, and represent so much wasted magnetism. This leakage might even be greater than the small advantage gained by the extensions.

Another device for rendering the dead wire active, is to place in the inside of the ring an additional fixed electromagnet, whose poles are situated opposite to the other pole pieces, and have the same polarity as the corresponding pole pieces on the outside, thus making the wire on the inside cut lines of force in the proper direction. If this magnet is not very powerful it will short circuit magnetically the outside pole pieces, and in that case do more harm than good. This device, as well as the one abovementioned, is impracticable, as it complicates the construction very greatly.

The best method, and one which has proved to be very successful in practice, is to make the ring flat, like a disc with a large hole in it, the pole pieces being then at the two flat sides. Electrically, this is equivalent to putting an extra magnet in the inside of the ordinary form of Gramme ring, as it renders both of the long sides of the rectangular armature coils active, and it has moreover

the advantage that it does not complicate the construction. These so-called "flat-ring" machines are used very largely in Germany. The Brush armature is of this type, but has its coils connected differently. The most economic form of cross section of such a flat-ring machine would appear to be a rectangle in which the long side is two or three times the shorter; by making it much more than this the diameter of the armature is increased too much, or else the speed of those parts of the coils which are nearest the axis is too small.

In regard to the shape of the cross section of the ordinary Gramme armature core, no general rules can be given, as it will depend greatly on the general construction of the machine. The size of the cross section having been determined as described in considering the magnetic effects, it is well to make the length parallel to the axis as great as practicable and the thickness correspondingly small, for by doing so the required length of the wire on the armature will make less windings in a coil, thereby diminishing the self induction, the sparking and the thickness of the non-magnetic space between the core and the pole pieces, besides increasing its area. For the same reason, if it is required to increase the cross section of the armature, it is in general preferable to increase the length parallel to the shaft rather than to increase the thickness. For a given thickness, the magnetism increasing in proportion to the length of the armature core, it is evident that the electromotive force will be approximately proportional to the length of the core, other conditions being the same. This rule is merely a different statement of the rule given before, that the electromotive force is proportional to the magnetism passed through by the wire, it being understood that the iron of the armature and magnets is also increased in the same proportion, in order to be saturated to the same degree.

For a given cross section of the core the distance around the outside, that is the length of one winding, will be least,

if the cross section is circular. It might therefore appear that this is the best shape of the cross section. If the magnets and pole pieces were of such a shape as to surround this circle as completely as possible, it would no doubt be an economical form; but at the same time it greatly increases the difficulties of construction, and as it is difficult to make the windings on the armature as smooth and regular, it necessitates an increased distance between the core and the pole pieces, which is a very bad feature. In general, the cross section will depend on the general style of the machine, and therefore the best shape should be found by choosing from calculations made for several assumed shapes.

The core of an armature should not be hollow, for it is evident that if the hollow core is not over-saturated, the length of the wire around it, and, therefore, its resistance, could be made less by making the cross section solid but of the same area of cross section of iron as before. On the other hand, if it is over-saturated when hollow, the magnetism will be increased by filling the hollow space within it with iron, thus making it solid.

The diameter of the armature should evidently be as great as practicable, for by increasing it other parts may be decreased. For a given electromotive force, all other conditions being the same, an increase in the diameter will affect the other proportions as follows: the speed may be decreased in the same proportion; the number of windings or the length of wire (in a Gramme armature), and, therefore, also the distance between the armature core and the pole pieces, may be decreased in about the same proportion; or the latter may remain the same and the cross section of the wire increased, thus increasing the allowable current of the machine in about the same proportion; either the intensity or the size (volume) of the magnets may be decreased in about the same proportion; besides these, the distance between the projecting ends of opposite pole pieces may be increased in the same

proportion, thus decreasing the leakage of magnetism; the length of the armature core may be decreased in the same proportion; the weight of the armature core will be increased in the same proportion, in the case of a Gramme ring with a certain cross section of core, while in the case of a cylinder armature the weight will be increased as the square of the diameter.

From the last two statements, and from the fact that the whole machine is sometimes increased in size with a larger diameter, it is seen that a limit is soon reached to which the diameter may be economically increased. In this case, as well as in the case of several other proportions, it is best to assume different values for the diameter, and calculate the other parts affected by it for each case, from which the best proportions can then be readily chosen.

The general rule in regard to speed or number of revolutions, is to make it as great as practicable. Its limits are, in practice, purely mechanical, as there is no reason, electrically, why the speed should not be very great, except that the electromotive force of the Foucault currents and the resistance to changes of magnetism in the armature core are thereby greater, thus requiring finer laminations of the iron and softer iron in the core; but neither of these two will be as important in limiting the speed as the mechanical considerations. For a given electromotive force, all other conditions being the same, an increase in the speed will affect the other proportions as follows: the diameter may be decreased in the same proportion; the number of windings or length of wire on the armature, and, therefore, also the distance between the armature core and the pole pieces, may be decreased in about the same proportion; or the latter may remain the same and the cross section of the wire increased, thereby increasing the allowable current in about the same proportion; either the intensity or the size (volume) of the magnets may be decreased in about the same proportion; and in conjunction with this the breadth of the pole pieces

measured on the circumference of the armature may be decreased if they are not over-saturated, thus increasing the distance between the projecting ends of the two opposite pole pieces and thereby decreasing the leakage of the magnetism between these parts; if the amount of magnetism is decreased, either the length, the thickness or the cross section of the armature core, or what is the same thing, the weight of the armature core may be decreased in about the same proportion.

The mechanical considerations for high speed are as follows: The armature should be as light as possible. Its diameter should not be too great. The shaft should be large in diameter to resist all tendency to bending. The length of the shaft between the bearings should be as short as possible to prevent bending, and, therefore, vibrating and causing a trembling of the machine. The bearing at the pulley end should therefore be between the pulley and the armature, not outside of the pulley. The armature and commutator between the two bearings should be as short as possible, and there should be no lost space between them or the bearings. The bearings should be long, at least three to five times the diameter of the shaft; and they should be made of some anti-friction metal; in no case should bearings be of iron when the shaft is of iron or steel, on account of the tendency of the magnetic attraction to increase the friction by pressure. The bearings should be as free from magnetism as possible, to avoid the generation of Foucault currents in the shaft, which are necessarily short-circuited through the centre of the shaft, and therefore may be very intense, and then heat the bearings. The bearings should be bored as true as possible and preferably bored at the same time with the pole pieces. They should preferably be fastened directly to the pole pieces and not bolted on a base plate on which the machine is fastened, as they are then liable to be out of line. The supports of the bearings should be as rigid as possible to prevent vibrating or trembling. It is of special importance

in high speed that the armature should be rigidly connected to its shaft, and that it should be well bound to prevent bursting, or to prevent the wires from bending outward by centrifugal force, thereby coming into contact with the pole pieces; the tie bands around the armature wire should therefore be very tight and strong, and not too far apart. The armature should be as smooth as possible on the outside to prevent churning the air. The commutator should have as small a diameter as practicable to prevent too much motion between it and the

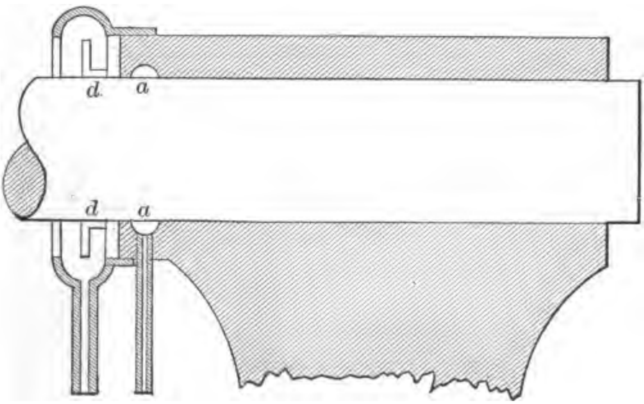


Fig. 10

brushes. It is preferable in cases of high speed to allow the shaft to have a slight lateral play of $\frac{1}{2}$ or $\frac{1}{4}$ inch, as it then distributes the oil better and is not so apt to cut the bearing. In this case the machine should be shifted on its foundation while running with its full load, until the shaft has a free lateral motion, as the position of the machine to allow this free lateral motion may be different when running with a full load than when running without

a load, on account of the magnetic attraction of the armature and its field magnets. The distance between the armature core and the pole pieces should be precisely the same, on both sides, otherwise the armature will be attracted with very great force to one pole piece when the field is strong, thus bending the shaft and heating the bearings. As the oil has a greater tendency to get on to the armature and commutator when the speed is great, it is preferable in that case to have an oil catcher or screen of some sort between the bearing and the armature and commutator. The simplest form is to make a groove in the inside of the bearing with a dripping tube at the bottom, as shown at *a* in figure 10. Another simple and effective device is to fasten a thin disc to the shaft near the inside end of the bearing, as shown at *d*, figure 10. The oil must pass around this disc to get to the armature, and as the disc revolves with the shaft the oil is thrown off at the edge by centrifugal force, and will therefore not get on to the other side. It may be caught and collected by a grooved ring and dripping tube, as shown.

Besides these considerations in connection with high speed, it is especially necessary to have the armature perfectly balanced mechanically, for if it is not balanced it will be liable to vibrate, which will be augmented by the consequent unbalanced magnetic pull of a strong field on the armature, due to the core vibrating, so as to come nearer to one pole piece and farther from the other. This vibration may become great enough to abrade the surface of the armature on the pole pieces, which is apt to cut the tie bands, resulting in the short circuiting and the total destruction of the armature. To balance the armature statically, place it, when quite completed, on two horizontal "knife edges" so that it rests near the two ends of the shaft. If on rolling it slightly it comes to rest in any position, it is balanced, if not, weights must be added securely, or better, metal must be removed if possible, so that it will come to rest in any position. It is often

thought that this method of balancing is sufficient, but this is not the case, for an armature may be balanced perfectly on knife edges and yet it will vibrate when running at high speed. This will be seen from figure 11. Suppose there is an excess of weight at w and an equal amount at a diametrically opposite point w' but at the other end. It will be balanced perfectly on the knife edges, but when revolving there will evidently be a tendency to distort the

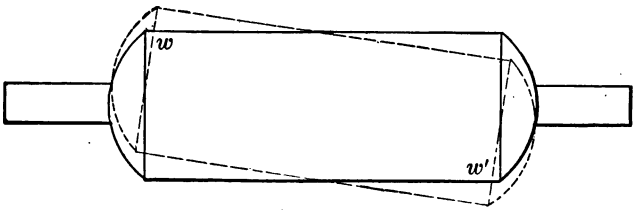


Fig. 11

shaft and armature as shown in dotted lines, which will tend to cause vibrations at the bearings. It is similar to the case of a bicycle wheel which may be balanced statically or when revolving slowly, but when revolving rapidly it will tend to vibrate, which is due to the weight of the cranks and pedals at two diametrically opposite parts at the two ends. In the case of an armature, it may be detected in several different ways, one of which is to revolve it rapidly while resting on two bearings, which are suspended and are free to move laterally.

An increase in speed represents a saving of material and a decrease of resistance in the armature and magnets; it is, therefore, a direct gain, both in cost of material and to a certain extent in efficiency, and consequently it is of equally great importance to take as much care with the mechanical details of construction as with the purely electrical proportions. It is much easier to build a low speed dynamo, as defects in its construction may exist which would be fatal

to the successful running of a high speed dynamo. The aim of the technical engineer is to find the most economical proportions, while the aim of the manufacturer is to find the cheapest form. As the proportions and the cost of material both decrease with an increased speed, the importance of careful attention to necessary details of construction limiting the speed, becomes evident. Many mechanical machines are in continued daily use which are run successfully at a much higher speed than dynamos. The success of a certain well-known machine which is electrically deficient, is mainly due to the exceptionally high speed at which it can be safely run.

CHAPTER V.

Armatures.—(Continued.)

The electromotive force induced in the armature depends directly on the velocity with which the active parts of the wire move through the field. This is commonly known as the "conductor velocity," though it ought properly to be called the "inductor velocity," as the wires moving through the magnetic field are the "inductors," or those in which the induction takes place; while the wires at the ends, and in the inside of a Gramme ring, are the conductors, as their only function is to conduct the current which is generated in the inductors. This inductor velocity will be greater as the distance of the moving wire from the shaft is increased, and as the number of revolutions is increased; in other words, the inductor velocity depends both on the diameter (or radius) of the armature, and on the number of revolutions; it is not a function of either alone, but depends on their product.

This inductor velocity should evidently be as great as it is practical to make it, for increasing it represents a direct gain in other parts. It is usually measured in feet per second, and may be calculated by multiplying the circumference of the armature, in feet, by the number of revolutions per second. As the diameter of an armature is usually given in inches, and the speed in revolutions per minute, the calculation may be simplified by multiplying the diameter in inches by the speed in revolutions per minute, and by .0044 approximately (accurately, .004363), which gives the result directly in feet per second. If greater accuracy is desired than that obtained by using the external circumference of the armature, allowance should be made for the thickness of the layers of wire, as the inside wires have a

somewhat less velocity; therefore, instead of taking the outside circumference of the armature, it is better to take the mean of the circumferences at the outside and at the inside layer.

As this inductor velocity is dependent on the product of the diameter and the speed, it may be increased by increasing either of these, but from the mechanical considerations it is preferable to increase the diameter rather than the speed, because in doubling the inductor velocity, for instance, it is easier to double the diameter and run at the same number of revolutions, than it is to keep the same diameter and run at double the speed. There is also another reason why this is preferable, for by doubling the diameter, and, therefore, the circumference or surface of the armature, the same number of turns of wire will make only half as many layers, thus decreasing the distance between the pole pieces and the core, and very greatly decreasing the proportion of this distance to the diameter of the armature. An armature of small diameter is, therefore, running at a disadvantage, for with the same length of armature, same speed, current and number of turns on the armature, the electromotive force, and therefore the capacity of the machine, may be doubled, and at the same time the number of layers halved, by doubling the diameter of the armature, the only other change being a larger field to embrace double the area of armature surface, and a somewhat greater amount of dead resistance.

The best guide in selecting the inductor velocity to be used in dynamos, is to compare the results of practice in well-built machines. In a number of the best Edison machines[1] it varied from about 46 to 54 feet per second, for cylinder armatures varying from 10½ to 7 inches in diameter, the speed varying from 1,100 to 1,600 revolutions per minute. With the latter high speed the inductor velocity was only 46.5 feet per second for a 7-inch

1. See table in Appendix I.

armature, showing, as stated above, that small armatures do not run as advantageously as larger ones. In several of the best Weston incandescent light machines, with 8 to 9-inch armatures and speeds from 1,050 to 1,250 revolutions per minute, the mean inductor velocity varied from 37 to 43 feet per second; while for some Weston arc-light machines it was as high as 61 feet per second. In a small Weston incandescent light machine with a 4½-inch armature, at 1,380 revolutions per minute, the mean inductor velocity was only 26 feet per second. A contrast to this small armature is the large 60 arc light Brush machine, which makes only 825 revolutions per minute, but has the very high mean inductor velocity of 72 feet per second, the mean diameter being about 20 inches, which shows the great advantage of large diameters of the armatures. Another flat-ring machine (Schuckert) had 65 feet per second. Hospitalier states that 66 to 82 feet per second for the middle part of the armature, is rarely exceeded; this, no doubt, has reference to Gramme armatures, and gives for the inductor velocity about 83 to 100 feet per second. A Siemens cylinder armature machine had as high as 107 feet per second, but this, as well as the previous one, no doubt exceeds good engineering practice. As a rule, Gramme armatures are lighter and larger in diameter, and can therefore be run at a higher inductor velocity than cylinder armatures, which is an important advantage over the latter.

One of the principal proportions in armatures is the relation between the length of the armature wire and the electromotive force which it is to generate. Although this is of such great importance, there is, strange to say, little or no practical information regarding it given in the numerous text-books. Elaborate theories and complicated formulæ have been published, but it is doubtful whether they are of much value in practice. The most reliable proportions are, no doubt, those which may be deduced from some of the best existing machines. The writer has,

therefore, calculated some constants from the proportions of some Weston and Edison machines, which, though taken from entirely different machines—both arc and incandescent—agree so well that they can safely be taken as a reliable guide in determining what length of wire is required in the armature, to give a certain required number of volts. These machines were all of the cylinder armature type, but it is presumed that, if properly applied, the constants may also be used for Gramme ring armatures.

As stated in a previous chapter, the electromotive force is induced when a wire cuts lines of force, and therefore only that part of the wire is generating electromotive force which lies directly between the pole pieces and the armature core. This will be termed "active wire," in distinction to the dead wire at the ends of the armature, and that which is not embraced by the pole pieces. A few lines of force pass around from the outside of the pole pieces to the ends of the armature, thus rendering part of the otherwise dead wire active; some also pass obliquely from the thin ends of the pole piece projections to the armature core, thus rendering active some of the wires which are not directly between the iron of the pole pieces and the armature core. But as the intensity of the field is, or should be, so very much greater in the space lying directly between the pole pieces and the armature core, the small amount of induction in the other parts of the wire may be neglected. With this assumption, it was found that in several Weston incandescent light machines the total electromotive force generated was at the rate of from 1 to 1.3 volts for every foot of active wire, while from some rough measurements of several arc light machines of the same type, it was from 2.2 to 3.2 volts per foot, with a higher inductor velocity and a more intense field. In several Edison machines, of different sizes, it was from 1.5 to 1.8 volts per foot. It is assumed, in deducing these constants, that the field is uniform in all parts; this is probably not the case, but it will not materially affect the values

of the constants, as they may be taken to represent the average value for all the wires. Moreover, in calculating armatures, these constants are to be applied to conditions similar to those under which they were deduced, and the error will, therefore, be eliminated.

The electromotive forces induced per foot, as just given, depend on the speed as well as on the field. In order, therefore, to properly compare the results, and to reduce them to a form in which they may be used for different speeds, it is necessary to eliminate the speed, or, in other words, to divide these constants by the inductor velocity in each case, thus reducing them to the number of volts which would be generated if the active wire on the armature had a uniform velocity of one foot per second. In the Weston incandescent light machines this reduced constant was .025 to .030, which means that in every foot of active wire on the armature, .025 to .030 volts would be generated if the wire had a velocity of one foot per second. As the electromotive force is directly proportional to the speed, this constant must be multiplied by the velocity of the moving wire of any particular armature, in feet per second, to give the number of volts per foot which will be generated in that armature when running at the desired speed. In several Weston arc light machines, a rough measurement gave from .044 to .052 volts per foot for an inductor velocity of one foot per second, showing that the field was still more intense than in the incandescent light machines. In several Edison incandescent light machines of different sizes, it was .033 to .037, showing that the field was more intense than in the Weston incandescent light machines, but not as intense as in the arc light machines.

As these constants agree tolerably well with each other, they may be safely used in designing armatures for machines where the general construction is similar to these machines. Probably they could also be used for Gramme armatures, provided that only the active wire is considered,

and that the magnetic field can be made as intense as in these Weston and Edison machines. The core of the Gramme armatures will, therefore, in most cases, have to be made larger than is customary, in order not to weaken the field by interposing too much magnetic resistance in the armature. How to apply these constants in designing armatures for generating a required electromotive force, will be more fully explained and illustrated in a subsequent chapter on the calculations of armatures.

These constants evidently depend directly on the intensity of the field, and vary with it, for if the intensity of the field were doubled, the values of these constants—that is, the number of volts per foot—would also be doubled. The magnetic fields of dynamos will be considered later; it will suffice to state here that the fields of the Weston machines had an intensity of magnetism of 18,000 to 21,000 useful lines of force per square inch of pole piece surface, while in the Edison machines this intensity was from 23,000 to 26,000; these higher figures are probably due to wrought iron being used in the field. In cases where the field is as economically proportioned and as well designed as in these machines, an intensity equal to these figures can be used in calculating armatures; but if the field is not as well designed, it is advisable to use a smaller intensity in calculating armatures, in order to be on the safe side.

Another important proportion in designing armatures is the size or cross-section of the wire used. This evidently depends on the current which is to flow through the machine and also on the amount of electrical energy which is to be lost in the armature. It is not simply dependent on the current, but is governed also by the number of volts per foot which are to be generated in the wire ; for suppose, for instance, that four per cent of the total electrical energy is allowed as loss in the armature, which will be a certain number of volt-amperes or watts, and will represent a certain definite amount of heat which must be dissipated

on the surface of the armature ; from the constants given above for the induction per foot, the required length of wire can be calculated and from this length together with the volt-amperes which may be lost in it, the resistance and cross-section of the wire can readily be calculated. Now it is evident that if by any means this induction per foot of wire may be increased, for instance doubled, the length of the wire may be halved, and therefore, to have the same resistance, the cross-section may also be halved, which will decrease the amount of wire by weight to one-quarter of what it was before ; now if the size of the cooling surface of the armature remains the same, that is, if the number of layers have been reduced to about one-third of what they were before, the size of the armature remaining about the same, the armature will not get any hotter, as the amount of heat generated is the same and the cooling surface the same. The cross-section of the wire for carrying the same current has, therefore, been reduced to one-half of what it was before, without heating the armature more. This calculation will be modified somewhat, on account of the resistance of the dead wire in the armature, which was not considered in the above statement in order to avoid complication of the calculation. The great importance of increasing as much as possible the number of volts per foot is seen from the example just given, in which it was shown that in doubling the induction per foot, by increasing the speed or the intensity of the field, the amount of active wire, by weight, is reduced to one-quarter of what it was, for the same loss in the armature and the same current. This also represents a decreased self induction (provided the speed is the same), less sparking at the commutator, less counter magnetism of the armature, and less shifting of the brushes, provided the outside dimensions of the armature remain approximately the same. There will also be an increased intensity of the field, as the space between the pole pieces and the armature core has been reduced to about one-third of what it was.

In order to serve as a guide in preliminary calculations of armatures, certain values for the proportion of the cross-section of the wire and the current are sometimes given. A common rule is to use about three amperes per square millimetre cross-section, in which it must be remembered that only half of the current flows through a wire on the armature, because the two halves are in multiple arc. This, reduced to a more practical form in our own units, is equivalent to 520 square mils per ampere. In the Weston and Edison machines mentioned above, the following proportions exist: in the Weston, from 375 to 562 square mils per ampere; and in the Edison, from 400 to 500, where a single wire is used; and 475 to 600 for the sum of the cross-sections where two and three wires were used in multiple arc. These figures being taken from the same machines from which the constants given above for the induction per foot were calculated, they may be used in armatures in which the induction is about the same as in these machines.

Another important point in designing armatures is the thickness of the space occupied by the wire on the armature. As this depends on so many of the other proportions, such as the cross-section and length of wire, the diameter and length of the armature, the induction per foot, the speed, etc., it is hardly possible to give any definite rule. The general rule, already given in a previous chapter, is to make it as small as possible. The following constants taken from the Weston and Edison machines may serve as a guide. The percentage of the external diameter of the armature which is taken up by the windings on both sides (or in other words the double depth of the winding divided by the external diameter) was as follows: in the Weston machines 8 to 10 per cent. and in the Edison, 8.8 to 11.5 per cent.; that is, in a Weston armature of say 10 inches external diameter, the wire would occupy from .8 to 1 inch, making the thickness of the layers from .4 to one-half inch. Possibly this depth may be increased without decrease of effect, if iron lugs or projections are placed between the

coils as in the Pacinotti ring armature, but this point we believe has not yet been conclusively demonstrated.

The distance between the pole piece projections where they are nearest to each other, depends on the distance between a pole piece and the iron core of the armature, that is, on the depth of the armature windings and the clearance between the armature and the pole pieces ; for it is evident that the lines of force at this part of the field have the choice of two paths, either from one pole piece to the core and then from the core to the other pole piece, or else directly from one pole piece to the other ; in the first case they are rendered useful as they are cut twice by the armature wire, while in the latter case they are wasted, and represent leakage of magnetism. Suppose the distance between the pole piece projections was equal to twice the depth of the winding and the clearance, then the intensity of the field between them would be as great as the useful field between the pole pieces and the armature core at that place, and would, therefore, represent a considerable waste. The amount of this leakage would be dependent on the amount of surface exposed on the ends of these pole piece projections. The distance between the pole piece projections should be made as many times the depth of the windings as possible, not only on account of the leakage, but also to make the field as weak as possible, for the armature coils lying between these pole piece projections, as these coils are the ones which are short circuited by the brushes, and should be as free from induction as possible. To make this distance too great would diminish the amount of active surface of the armature too much. Perhaps the best guide is, to make this distance a certain number of times the distance between the pole piece and the iron armature core ; about seven to eight times is a fair proportion. In the Weston machines it was found to be about 4.75 to 5.75 times, while in the Edison it was from 4.4 to 8 times. By making it great, say eight to nine times, the brushes, for an armature with comparatively few

windings, will require less, if any, adjustment for different loads, as the field is weakened in the place where the dead (short circuited) coils are.

Another rule for this proportion is, to make the distance between two pole piece projections about 10 to 12 per cent. of the whole armature circumference; this will make the active surface of the armature about 80 to 76 per cent. of the whole surface, a figure which is very convenient to use in preliminary calculations of armatures. This is about the proportion which exists in the Edison and Weston machines. In a certain 100 incandescent light compound-wound machine of 100 volts, in which the distance between two pole piece projections, was about 14 per cent. of the whole circumference, the sparking was almost completely avoided, and the brushes required no adjusting for different loads; it was impossible to see any increase of sparking when the whole load of 100 lamps was suddenly cut out or put into circuit. This shows the importance of allowing sufficient space between the ends of the pole piece projections.

CHAPTER V.

Armatures.—(Continued.)

In winding a Gramme armature, the following are among the most important points to be observed. The available space for the wire should be utilized as completely as possible, and therefore should contain no wooden or non-magnetic lugs or partition pieces, and as little as possible of the frame work necessary to hold the armature to the shaft, and no more insulating material than is necessary. The length of the wire should be as small as possible for the required number of windings, and therefore should be wound as closely as possible. The wire should be so wound as not to be liable to slip, one turn over another, or to change position after completion, as this loosens the winding, thereby causing abrasion and a resulting short circuiting in the armature. The successive layers should therefore, preferably, when practicable, be wound, as shown in figure 12, rather than as shown in figure 13, for in the latter case they

Fig. 12

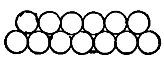
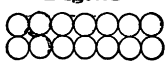


Fig. 13



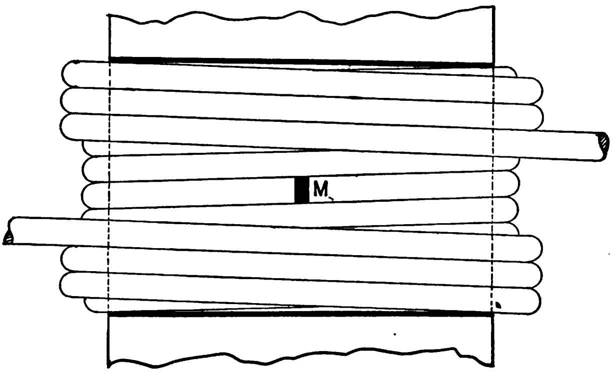
may slip into the position in figure 12, thus loosening the wire and thereby decreasing the external diameter of the armature; although this may be very little, yet in many cases it might be just enough to loosen the tie bands around the outside of it, which may result in serious consequences. It is preferable, particularly in high potential machines, that the wires at the beginning and end of the same coil do not cross each other where they are tightly pressed together, unless carefully insulated, because where two single wires cross each other they

touch in only one point, and it requires but a very slight amount of abrasion, or a slight blow, to crush the insulation and make contact, thus short circuiting that coil, and in many cases burning off the wires. Even if the insulation is not ruptured in such cases, a lightning discharge through the armature from an air line circuit, or a high self-induction spark, such as might occur when an accidental short circuit was suddenly broken, might "jump" through the insulation, thus starting an arc which the current of the machine would then maintain. An armature with few commutator bars and few coils of many turns is more liable to such an accident than one in which the windings per coil are few, and the electromotive force per coil correspondingly small.

In winding a Gramme armature in the ordinary way the wire from the beginning of the lowest layer has to pass to the outside between the coils, which in a well and closely wound armature will cause some irregularity in the winding owing to the space it occupies, particularly as it should have an extra insulation with tape. Furthermore, if this end breaks off short, as it is apt to do, the whole coil must be unwound. Both of these objections are overcome, while at the same time other advantages are gained by the following simple and ingenious winding which we believe is now largely used. Find the actual length of wire required for one coil, by winding it temporarily, cutting it to the right length, and then unwinding it. Cut the others to this length. Find the middle of the length of the wire for one coil, for instance by doubling it on itself, and mark this middle point. Start the winding by placing this middle point of the wire in the middle position of the first layer, as at M, figure 14, and having clamped or tied it, start with either end and continue winding just as if the middle point was the beginning of the coil, neglecting for the time the other half of the wire. The space for this first half of the coil when wound, must, however, be only half the width of the space for the whole completed coil. Having thus wound the first half, take the rest of the wire on the

other half of the middle, and wind it in the same way in the remaining half space for that coil, thus bringing both ends of the wire, that is, both the beginning and end of the finished coil, on the outside layer. If there is an odd number of layers, these ends will be at the two ends of the outside or last layer, thus being in the best possible position to be connected to the end of the previous coil and the beginning of the next, respectively. As this brings both ends of each coil on the outside layer, it overcomes some of the difficulties in winding a smooth compact armature, and has the great advantage that there is no irregularity in the winding, nor is there danger of short

Fig. 14



circuiting caused by the beginning of the wire passing out between the others from the lowest layer to the outside. It also has the advantage that in case the end breaks off it is easily spliced as it can readily be unwound for one or two turns. In practice when there are more than three layers it is preferable to wind the half layers successively, and alternately with each end of the wire, as illustrated in figure 14, thus completing each full layer before starting the next. If

the number of layers is even, the two ends of a completed coil will both be in the middle of the outside layer ; this, however, is not objectionable.

When iron lugs are used between the coils, it is preferable to make them wedge-shaped so that the sides of the space for one coil are parallel, as this facilitates the winding and makes it smoother. If there are no such lugs the coil space itself is narrower inside the ring than outside and there will be more layers on the inside than on the outside ; the winding will, therefore, not be quite as smooth at the curved ends but can be made to appear compact and smooth by placing a piece of cardboard under the last layer. Every dynamo builder takes pride in having handsome looking armatures, especially as a carelessly and loosely wound one carries with it the impression that the whole machine is built after the same fashion.

In order to make the winding smooth in cases in which no lugs are used, resort is often had to the device of placing strips of thick card board in the empty space in each layer on the outside of the ring, when the corresponding space on the inside is full, in order to make them come out even. But in cases of armatures of small diameter and many layers, this wastes valuable space and had therefore better not be done.

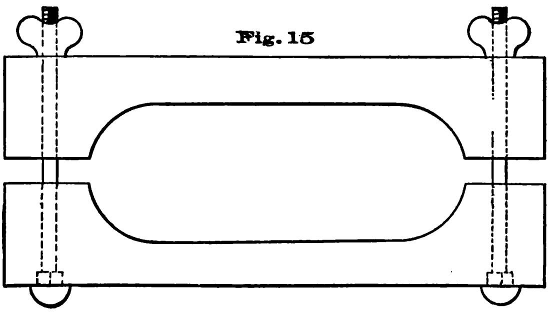
Prior to winding a Gramme armature the spaces for the coils should be accurately and carefully marked off in pencil on the outside of the core after it is thoroughly insulated with several layers of shellaced paper or muslin. It is bad practice to wind the coils without spacing them off properly and to let the last coil take up any difference, for, as pointed out before, it is very necessary that all the coils should be alike in every respect.

When there are no iron lugs to serve as guides, it will be found greatly to facilitate the winding to make two wooden clamps as shown in figure 15, the oblong hole in the inside of which fits the core tightly, one side of each of the clamps being radial to the centre of the core. These

are clamped securely to the core at the pencil marks of the space for a coil and serve to keep the coil in place while winding it. Two or three pieces of tape may be laid transversely in the troughs thus formed for the coil, and afterward closed over the outside of the coil when completed, thereby keeping it from collapsing when the wooden clamps are removed.

The end of one coil and the beginning of the next being fastened to the same commutator bar, the current in these coils has to pass through one of these, through the clamped or soldered contact at the commutator bar, and back through the other wire, in all of the connections except at the two or four where it flows off to the brushes. Although

Fig. 15



the resistance of each of these short lengths of wire, and of the soldered or clamped contacts, may be small, yet there are many of these resistances in series, and they may, therefore, form an appreciable part of a low resistance armature, especially when the contact with the commutator bars is not very good. It is therefore preferable to strip the insulation for a short distance on these two wires quite close to the coil, and either twist or bind them together and afterwards solder them. This is especially to be recommended in cases where the commutator is some

distance from the armature, as for instance when it is outside of the bearing.

Binding wires on the outside of the armature should be tightly wound and very well insulated from the wires, preferably with mica. It is better to make them narrow and at frequent intervals rather than broad and fewer of them, as currents are induced in them as well, and if broad, these currents have a chance to circulate through their very low resistance, thus heating them. If, as is usual, fine hard brass wire is used, all the wires of one band should be soldered together to avoid an uncoiling in case one of the wires is broken. Iron or steel tie wires should in no case be used as it would partially shield the core from magnetization.

Double covered wire only should be used for armatures. The windings should be shellaced, preferably with very thin shellac, while they are being wound. Armatures are frequently baked for a day to dry the shellac, especially when the winding is very open, as in spherical or carelessly wound armatures.

Iron wire has been suggested to replace the copper conductors, as it acts both as an iron core and as the conductor. But as the resistance is so much greater (about 6 times) it does not seem to have been a success in practice. Copper coated iron wire and copper wire covered with a thin layer of iron, have been suggested and we believe have been tried successfully.

The laminating of the core has already been described. It was shown that the best form was to make the core of thin discs separated by thin paper; but they are also frequently made of iron wire, which is first rusted to insulate it. The former is preferable, as the iron circuit of the lines of force in the core is then continuous, as distinguished from the course transversely to a bundle of round iron wires. In all cases the core as a whole should form a compact rigid mass; there should be no possibility of any parts of it becoming loose. Cast iron

armature cores, even when cut with slits are bad. The iron is always much inferior to the soft wrought iron of plates or wires; it is often harder; it increases the length and resistance of the wire as it is necessary to have a larger bulk of iron to produce the same magnetic effect, especially as the cuts are necessarily quite thick; it is apt to break, and if made at all well it is probably but little cheaper than wrought iron. A notable illustration is in the Brush machine which formerly had a cast iron armature core which is replaced in the present machines by a wrought iron one, increasing the capacity of the machine, we are informed, from 40 to 60 arc lights, or 50 per cent. The wrought iron armature is said in this case to be no more expensive than the cast iron one.

It is best not to trust too much to friction to securing the armature to the shaft, but to fasten it by some more reliable method. A very small amount of slip may do a great amount of mischief. It must be remembered that the whole horse-power driving the dynamo, acts to push the wires of the armature over the core in a cylinder armature, and to twist the core and windings off the shaft in a Gramme armature. The force to displace the wires is precisely the same in amount as if a brake band were gripped so tightly around the outside of the armature as to cause it to require the same force to turn the armature as when running in the field with its full load. When the armature is suddenly short circuited the sudden increase in this force to tear off the wires amounts almost to that of a blow from a hammer.

The core should have all edges rounded off smoothly, and should be thoroughly insulated with muslin, tape or paper, well shellaced.

The subject of the ventilation of armatures has, apparently, occupied much more attention among dynamo builders, than its importance seems to demand. The construction of armatures has been in many cases greatly complicated in order to convert the internal parts into fans and flues

for ventilating ; in one case the armature core itself was a sort of centrifugal blower sucking air in at the shaft and driving it out at the periphery. But to the technical engineer it cannot fail to be evident that it is much better to prevent the generation of heat in the armature by proper construction, than to sacrifice the efficiency by developing a large amount of heat, and then still further reducing the efficiency by using part of the power to mechanically dissipate this heat by forcing air through the armature. There will of course be some heat generated in the wire and in the core ; but by proper proportioning of the cross section of the wire, by proper lamination and insulation of the core, and by using soft wrought iron, this amount of heat may be made comparatively small ; by increasing the diameter of the armature to present a large external surface, this heat can readily be dissipated at such a rate that the temperature of the armature remains low enough not to be objectionable. There is no objection, therefore, to making the core of the armature compact, without flues or vents, provided it is proportioned so as not to heat too much. Practice has shown that in armatures without internal ventilation the resistance of the wire may be so proportioned that it absorbs from 3 to 4 or even 5 per cent. of the total electrical energy.

Commutators should be made with as many bars as practicable for reasons mentioned before, as the number of coils is the same as the number of commutator bars. The absolute number of bars depends on numerous proportions of the armature, and must, therefore, be determined in each case. As a guide may be taken the results of good engineering practice, which show that in incandescent light machines of somewhat over 100 volts the number of commutator bars is so proportioned that the mean number of volts between two bars, that is, the induction in one coil, is from 4 to 7 volts. In other words, if the machine is to give 120 volts, and it is decided to assume about 5 volts per commutator bar, and if 80 per cent. of the wires are

active, there will be $120 \div 5 = 24$ active bars on one-half, and as this is 80 per cent., the total number in one-half would be $24 \div .80 = 30$, making about 60 bars in all. In high potential arc light machines the number of volts per commutator bar must necessarily be taken greater as it would otherwise make the number of bars too great. The objection to a large number of volts per coil is not so great in arc light machines, as the current is always small in comparison to incandescent light machines, and the damage which a spark at the brushes causes decreases with the current. The long bright spark of a high tension and low current machine may not destroy the commutator nearly as quickly as the less bright spark of a machine giving a large current. Twenty volts is said to be the lowest potential that will maintain an arc; it is therefore preferable, if not almost essential, that the maximum volts per commutator bar should be less than 20, at least for those near the brushes, otherwise an arc between two bars may be established by the brushes which then continues to burn, causing the well-known flash encircling the whole commutator.

The thickness of the insulation between the bars should not be less than one fiftieth of an inch, as the danger of the "jumping" of the self-induction spark becomes too great if the distance is much less. In a case in which this was less the commutator was seen to be covered with myriads of small sparks, which, although doing little harm themselves, are too apt to establish more dangerous arcs. The material used for insulation should not be anything that will char, thereby being converted into conducting carbon; it should not be gritty as it then acts to wear off both the brush and the commutator; it should not wear off less rapidly than the bars, as it would cause the brushes to vibrate, causing sparking, and an objectionable humming noise. Air insulation between the bars is not good, except where the space can be made very large as in the Brush and Thomson-Houston machines, as it is too apt to

fill with copper dust or other conducting material, making contact between them.

The connection of the coils to the commutator bars are either soldered or else clamped with screws. The objection to the former is, that the whole armature has to be returned to the makers to have the commutator renewed, while the objection to the latter is, that the screws do not make such a good contact, and are apt to become loose and open the circuit. The choice between them is the choice between two evils. If the wire terminals are in the form of flattened loops, and if the screws are frequently overhauled, the latter is probably the better method. Rosin should always be used as a flux in soldering, in preference to acid, except when used by skillful and careful persons, as a drop of acid on the coil or core may do considerable damage in course of time.

For single machines, a commutator is easily made by casting it as a massive cylinder, turning it off to fit the holder and then cutting it into strips on a gear-cutting machine. These strips are then insulated and fastened together in the usual way with conically surfaced rings.

In order to bring the brushes, or the line of commutation into a convenient position, the connections to the commutator may be made at an angle, as if the commutator had been twisted at an angle with reference to the armature, after the connections were made. This is often resorted to as one of the "tricks of the trade," to make it appear as if the neutral line was exactly perpendicular to the axis of magnetization.

The brushes should not be made of wire alone, as they are too apt to cut grooves into the commutator, therefore necessitating frequent dressing of its surface. Nor should they be of solid sheets if they are broad, as they then do not always make good contact along the whole width. They should be cut lengthwise into narrow strips, and should, for large current machines, be quite thick. A good brush for incandescent machines, may be made with alternate layers of wire and sheets with longitudinal cuts

in it. A brush should not at any time touch more than two bars, except when there are very many commutator bars, and when the distance between the pole-piece projections, or the width of the neutral field, is very large. It is a mistake to think that when the brushes are pressed down very hard the sparking is diminished; on the contrary, this often increases the sparking. With well fitting brushes and a smooth commutator, it will suffice to have them touch very lightly only, provided they do not vibrate so as to leave the surface.

CHAPTER V.

Armatures.—(Concluded.)

CYLINDER armatures differ from the Gramme principally in the following respects. Their advantages over the latter are: for the same magnetism in the field the volume of the armature space, and, therefore, also the size of the dependent parts of the rest of the machine, is smaller, owing to the lost air space in the inside of the Gramme ring; the proportion of the wire on the armature which is active, is greater, that is, for the same field, electromotive force, current, and inductor velocity, the amount of wire required on the armature is less; for the same capacity of armature, the internal resistance is smaller; when thick wire is used for the windings, it is more easily handled than in the Gramme; it is easier to fasten the core rigidly to the shaft, without the loss of valuable wire space around the core; they are more easily centered or balanced accurately for high speeds; the core, if made of sheet metal, is less expensive, as there is less waste; an unbalanced field, that is, one in which leakage or other causes make one pole stronger than the other, will affect it less than it would a Gramme ring.

The disadvantages are: it is more difficult to insulate the wires for high potentials, as two neighboring wires may have the whole difference of potential of the machine in them; a high inductor velocity is not so easily obtained without great increase of weight of armature, as its weight increases with the square of the diameter, while in the Gramme it increases merely as the diameter; if one coil burns out it will often necessitate the unwinding of several others, or even of all the others, as the injured one is frequently among the first or inside coils; it is almost

impossible to have all the coils symmetrically situated and of the same length; for the same cross-section of armature core, it presents less external surface for the induction wires; it is more complicated to wind properly, and therefore requires a more skilled mechanic.

In designing cylinder armatures the following points are the most important, besides those already given. The greater the length as compared to the diameter the greater will be the proportion of active wire. On the other hand, the greater the diameter the higher will be the inductor velocity, which it is desirable to make as great as practicable. Both diameter and length should therefore be made as great as practicable; but as a practical limit is soon reached, it is necessary to determine by trial calculations for each special case, which of the two advantages has the greater weight. For high potential machines in which a slightly greater amount of dead resistance is not very objectionable, the diameter might be increased, while for low potential, quantity machines, the amount of dead resistance is of more importance, and therefore it might be better to increase the length of the core. As other considerations may however have greater weight in special cases, no general rule can be given.

The coils should all have as nearly as possible the same length and resistance, and should all be symmetrically situated with respect to the field and to their mean distance from the centre of the shaft. The difficulty of accomplishing this is comparatively great, and it is therefore of the utmost importance to guard against irregularities of winding, for, as stated before, if the electromotive force induced in one half of the armature is greater than that in the other, even if only a small amount, a current will circulate, on open circuit, in the armature wire itself, which by Ohm's law is equal to this difference of electromotive force divided by the resistance of the wire, and as the latter may be very small, this wasted current may be quite great. On the other hand, if the inductions in the two

halves are exactly equal and the resistances unequal, the differences of potential at the ends of the two halves (that is, the total electromotive forces, less that absorbed by the armature wire itself) will be unequal when the machine is running with a load, and there will be irregularities or pulsations in the current which may increase the sparking.

A coil should not be too wide, measured along the periphery of the armature, in order that the coil which is short circuited by a brush may be entirely in the neutral part of the field. The real neutral field is always considerably smaller than the distance between the pole piece projections. The coils should, for the same reason, be wound so that the two sides are as nearly as possible diametrically opposite to each other, though they need not be exactly opposite.

As the wires have to cross over one another at the ends of the armature, they occupy considerable space there, and make what is termed the "heads." It is evidently well to make these as small as possible, for several reasons; it shortens the shaft and the distance between the bearings, thus decreasing the width of the machine; it shortens the bearing braces or supports and reduces the tendency to vibration as the shaft is thereby stiffened; it makes the length or resistance of the different coils more nearly equal, as the lengths gradually increase from the lowest, or first coil, to the last, and with large heads this increase is evidently considerable; a small head is more likely to be flat, therefore diminishing the tendency of the wire to slip off and loosen the coil; it will facilitate making the windings compact and solid to have a small head. In order to reduce this head, the number of windings should be as small as practicable; the number of crossings should be as few as possible, and the turns of one coil should therefore be parallel and not cross over one another; the wires of the head should be bent around so as not to bring several crossings over each other, that is, the crossings should be distributed over the head so as to keep it as flat as possible.

When wires at the head are unavoidably in such a position as to be likely to slip, they should be tied with strong twine or tape, in order to hold them securely in their places. All wires crossing each other should be particularly well insulated with tape, shellaced muslin, fibre, or dense shellaced cardboard which is not likely to break.

The general principle of the cylinder winding is as follows. If, as in figure 16, a cylinder be supported on its axis, and while turning slowly, a wire be wound over it

Fig. 16

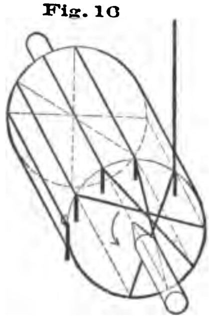
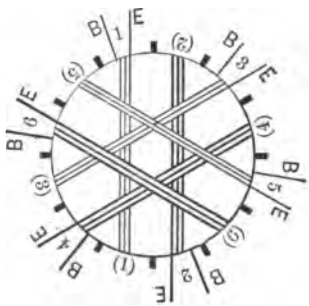


Fig. 17



lengthwise, it will, after having made one complete revolution, be wound with the simplest form of a cylinder winding. To complete it, the end of the wire must be connected with the beginning to make it an endless wire, and the beginning of each turn, or number of turns forming a coil, must have a branch wire attached to it for connecting it to the commutator, as shown by the bold lines.

In continuing the winding shown in this figure, it will be found that after a few more turns the armature will be completely covered with the wire, while the winding has been continued for only one-half of a revolution of the cylinder. Furthermore, the commutator branch connections will be found to be along only half the circumference,

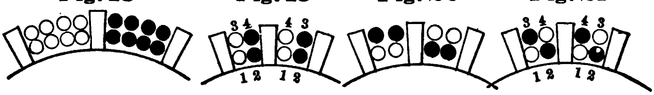
while the beginning and end do not meet and cross, but are parallel and in the same direction, so that they cannot be joined properly. This is often misleading and confusing to any one winding a cylinder armature for the first time, as it gives the impression that there is some mistake. It will be easily understood if we remember that the winding must be continued for one complete revolution of the cylinder, and as it is entirely covered after half a revolution, it follows that in the second half revolution the wire will have to be wound over that already on the cylinder, thus making two layers over the whole surface.

This simple form of cylinder winding has the objection that the coils of the second half are longer and larger, having a greater mean radius and, therefore, a greater velocity, as they are wound over the others. This, as stated before, is a fault which should be avoided, if possible. It can be overcome to a great extent by dividing the surface of the armature into the proper number of sections, as shown in figure 17, and winding at first only in every alternate section, until half of the whole number of coils are wound, as shown in light lines, and then continuing the winding of the rest of the coils in the remaining alternate sections, as shown by the dark lines. All the coils will then be symmetrically situated, will have the same mean radius, and more nearly the same length. This method will answer very well when there are numerous turns in each coil, or in general when the width of the cross-section of a coil is greater than its depth, as shown in figure 18, in which the dark and light sections represent the neighboring coils which belong to diametrically opposite commutator bars, as shown in figure 17. This proportion of the sides of the cross-section will generally be found to exist when the number of coils or commutator bars is small.

In the better class of machines this is however not generally the case, as for instance, when there are two turns per coil, for then the depth is greater than the width,

as shown in figure 19, and there may be difficulty in keeping the coils from collapsing while they are being wound. The method shown in figure 20, is often resorted to in such cases, but it is not to be recommended except when there are very many coils or commutator bars, as they have different mean radii from the axis. The difficulties mentioned have all been overcome by the ingenious method devised by Weston, and shown in figure 21, in which each coil is split into two equal parts, which lie alternately over and under the corresponding parts of the other coil belonging to the diametrically opposite commutator bar. In this method the turns are wound in the order as indicated by the numbers, either as in the first section or as in the second, the latter being less confusing while winding and the former simpler to the experienced winder. The advantages of the

Fig. 18 Fig. 19 Fig. 20 Fig. 21

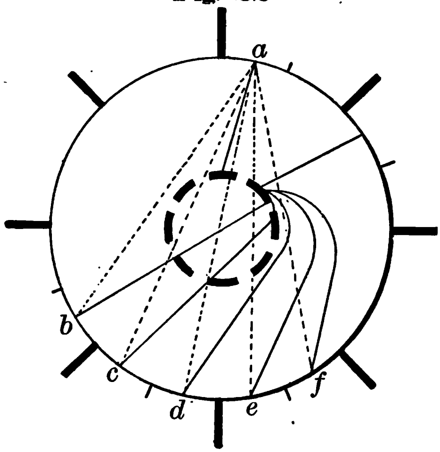


Weston system over the others increases with the number of turns per coil, and decreases with an increase in the number of coils. In the method in figure 19, the order of the winding may be either as shown by the numbers in the first section, or by those in the second; the former is less confusing, while the latter is simpler.

Referring to figure 22, which shows an end view of the unwound armature with eight sections, each for two coils belonging to opposite commutator bars, if we start at the first upper commutator bar, and wind into the first section *a*, we may return to the face in any one of the opposite half-sections *b*, *c*, *d*, *e*, *f*, thence to the next bar and the next but one half-section as shown. By returning in the diametrically opposite part *d* it will be seen the old Siemens winding, which, as will be seen by completing the winding,

is slightly irregular.[1] By returning in *e*, or *c*, it will be the Froehlich or Breguet, which are practically identical ; both are quite regular. By returning in *b*, or *f*, the winding becomes very irregular and should not be used. If the number of coils is odd, the Froehlich and the Breguet systems merge into one, that is, the half-sections *e* and *c* become one and the same, being then in the position of *d*, diametrically opposite to *a*. This is known as the Edison

Fig. 22



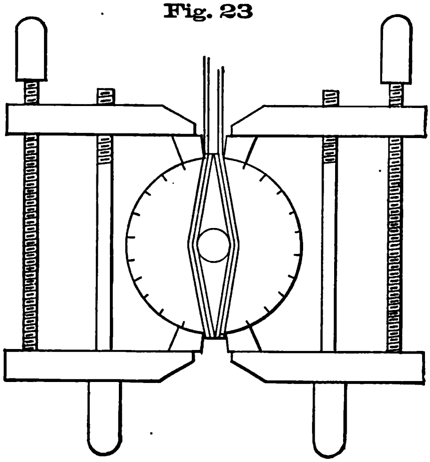
system. The Weston system is the old Siemens improved by splitting the coils as described. The writer's system is this same principle applied to the Froehlich, and is, therefore, quite regular and symmetrical. The chief advantage of the Froehlich over the Siemens, besides its regularity, is, that there are only half as many crossings of the coils on the ends, thus making smaller heads.

When iron lugs or projections are used between the

1. A detailed discussion of these forms of windings will be found in the ELECTRICIAN AND ELECTRICAL ENGINEER, March 1886, p. 84. See Appendix IV.

coils, the winding becomes less difficult. In that case each layer in one section (which may embrace from one to five or six coils) should be completed before the next layer is wound, thus frequently necessitating a number of coils being wound at the same time ; or, if this is confusing, a pair of wooden blanks should be made of exactly the width of the vacant part of one section, and be fastened there until the coil is completed and bound with tape.

Fig. 23



When there are no lugs or projections of the core, the surface of the armature should be carefully spaced off into the required number of sections. It will then be found convenient, if not essential, to make wooden blanks of exactly the width and shape of the section of a coil, and clamp them as shown in figure 23, leaving a trough of the exact width of one coil. In this case, it is advisable to wind first every alternate section and bind the finished coils with tape, in order to leave vacant spaces for inserting these wooden guiding blanks. When the armature is

half wound it will present the appearance of a cogwheel, with a trough between every two sections; these troughs being of exactly the width of a coil, are then readily wound with the remaining number of coils.

In winding the simple form shown in figure 17, in which each coil occupies the whole depth, proceed as follows: Suspend the armature core with its shaft on two high lathe centres, or on two similar centres between two strong posts, and jam it so tightly that it requires some force to revolve it. Select from figure 22 the method which is to be used; divide the armature surface into the required number of sections and mark on it, with the same number or letter, the two opposite sections which are to contain the first coil; similarly for all the others as in figure 17. Then, if there are partitions between each of the coils, as in figure 17 or 18, start at the upper section No. 1, and wind one coil, connecting its end temporarily with its beginning, and marking them, if desired, B and E. Then turn the armature around half a revolution, and starting in the same way wind the neighboring coil No. 2, figure 17, precisely similarly, connecting its ends together and marking them as before. Then turn the armature again for half a revolution and wind No. 3, and proceed thus, turning the armature one-half a revolution after each coil is completed. When it is completed, there will be a regular series of beginnings and ends of coils along the periphery of the armature, and they will all be in their proper relative positions. Untie the ends and connect the one marked E (end) of any one coil with the *next* one marked B (which will be in the next but one section) and with one commutator bar; the one marked E of this coil connect with the next B, and so on. By winding it as described it will be found to be almost impossible to make a mistake in the connections or in the proper location of the coils belonging to different sides of the commutator.

Another method is to wind first, sections 1, 3, 5, etc.,

figure 17, *without* turning the armature through half a revolution each time; then winding the even numbers, beginning at the point marked 2. But this is not as good, as the distribution of the unequal resistances of the separate unequally long coils is not so well balanced as in the first method. When the heads are small this difference will be less.

In winding the coils as in figure 19, two coils should be wound at the same time. Cut two wires to the proper length, call one the light wire and the other the dark. Start with one turn of the light wire (marked 1), fasten it, turn the armature through half a revolution and start the first turn of the dark wire (marked 2); turn the armature again and wind the turn No. 3 with the light wire which completes that coil; turn again and wind the turn No. 4 with the dark wire, which completes that coil. If the order given in the second section is to be used, the only difference is, that the armature is not turned between windings 2 and 3, which are taken with the same wire; neither is it turned in that case, between winding 4 of that section and 1 of the next. In the first method it must be turned between every two windings whether they be both in one section or in two neighboring sections.

If there are no lugs, and the appliances in figure 23 are used, in which case every alternate section should be wound first, it is evident that if the winding in figure 18 is used, the armature should *not* be turned after completing a coil, as all will then be "light" coils until half of their number are completed; in the winding shown in figure 19, however, in which each section is a complete set of two coils, proceed just as if there were no alternate section omitted.

If the Siemens winding, or any of its modifications are selected, it must be remembered that there is a slight irregularity just after completing the winding of half the number of coils. If this is not noticed it may result in wrong connections or in the unwinding of some coils, or in

objectionable cross connections. In the Froehlich winding it is necessary to guard against winding into the wrong sections, as they are not diametrically opposite. In all cases errors are easily avoided by making a correct drawing first, numbering the sections and transferring these numbers to the armature core.

If by accident a coil has been wound in the wrong direction, provided its location is right, there is no necessity to unwind it, as it will answer just as well to connect it as if the beginning were the end, and the end the beginning. This applies to Gramme armatures also.

To examine an armature for wrong connections of the beginnings and ends of coils, which should always be done, place the armature north and south, put a small compass needle off to one side of it, about on a level with the axis, and test each coil as it comes into the vertical plane, with a tolerably strong current, by touching the two upper commutator bars, or the two upper connections. The compass should always deflect in the same direction. If it changes its direction of deflection, reverse the connections of that coil. It is not necessary to disconnect the commutator for this test, if the current is strong enough.

UNIPOLAR ARMATURES.

The term unipolar as applied to machines, has not reference to the polarity of the magnetic poles, as lines of force always have direction, and therefore two poles. It has reference, we presume, to the polarity of the armature which in such machines is always in one and the same direction, not reversed twice in every revolution, as in ordinary machines. The advantage thereby gained is that the currents will always be in the same direction in the armature coils, and it is therefore not necessary to have a commutator to cut out and reverse the connections of a coil just as it passes out of one field into the other, that is, just as the induced current in it will be reversed, as in

ordinary machines. All sparking is therefore avoided, as the circuit is never opened or altered in the machine itself. All the evil effects of self-induction are also avoided, as there is no continued starting, stopping, and reversing of current in the armature coils. The current from such machines is precisely like a battery current, free from the pulsations always accompanying ordinary machine currents. A telephone connected to a fine wire coil, which forms the most sensitive detector of pulsations in currents, fails to detect the slightest variations.

Strange to say, the unipolar machine in the form of Faraday's disc, was, we believe, one of the first electric machines for currents ever invented; yet it has not until quite recently been made efficient to generate a current of more than a very low potential.

The difficulty encountered in the old forms of unipolar machines was that the lines of force of the field could be cut only once by the inductor or armature, and that to obtain a potential greater than a volt or two, it was necessary either to increase the speed, intensity of field and size of armature to an impracticable degree, or else to couple a large number of machines in series. In the ordinary bipolar machines, the inductor is in the form of a coil, and therefore cuts the same field a great number of times in one revolution, generally over 100 times, thus making the potential over 100 times that obtainable from a unipolar machine with the same field and inductor velocity.

Siemens improved the unipolar machine, by making the armature a tube with a cylindrical pole inside and a hollow pole outside having the opposite polarity. The lines of force passing from one to the other are cut by the revolving tube, thereby generating a current in one direction in the tube, which was collected at the two ends. In this machine the pole areas were quite large, but it is evident that this does not increase the magnetism more than a very little, unless the magnets themselves are increased also. With such a machine about two volts were generated in a

tube several feet long. The current, which is limited only by the resistance opposed to the two volts, was naturally very great, being, we believe, several hundred amperes; the armature resistance is, of course, very small, the greater part being in the collecting brushes.

Forbes' improvement consisted in making an economical field of very great intensity and rotating a disc between the poles. Two such discs in two independent fields constituted a machine. The discs were of iron to increase the magnetism. The polarity of the two fields was such that the current was from the periphery of one disc to its centre, and *vice versa* in the other disc, in order to enable them to be connected in series by the shaft. The current was collected at the periphery of the two discs by numerous brushes. With two 10-inch discs this machine gave at 3,000 revolutions, about 5.5 volts on open circuit, and about 2.5 volts when giving over 3,000 amperes. If the internal resistance had been lower this fall of potential would not have been so great.

The difficulty in unipolar machines is to connect several discs, bars, or wires of one armature, in series with each other, that is, to make the same inductor cut the same field a number of times. In England, France, and Germany, numerous patents have been granted for such machines in which this difficulty was supposed to have been overcome by connecting the end of one of the bars or wires of the armature, permanently to the beginning of the next by a wire, thus connecting them in series. This, however, will evidently not generate any useful electromotive force, as this connecting wire must in all cases in which the connection is permanent, also cut lines of force, and exactly the same number which the inductors cut, but unfortunately for the inventors this induction must necessarily be in the opposite direction, thus completely neutralizing the other electromotive force induced. It has been suggested to make this connecting wire pass through a weaker field, thus allowing the difference of the two opposing

electromotive forces to appear at the brushes. This is also inoperative, because wherever the same lines of force make a less dense field, it must be larger in area, that is, it has the same number of lines of force. It has been suggested to shield these wires by an iron tube, but as this tube also cuts lines of force, they must also pass through its centre, that is, through the wire.

A machine was devised consisting of a Gramme ring without a commutator, the wire being cut in one place and led to two collecting rings. One pole completely encircled the outside of the ring, while the other, a revolving pole, was permanently connected to the iron of the ring by arms extending in between the coils. The ring was then rotated. It was supposed that the lines of force would pass out of the core between the wires, and thus would not be cut in the reverse direction by the same wire. But as might be supposed the lines of force did cut the wire in two opposite directions. In a small model constructed some years ago by the writer, not the slightest current could be detected even by a sensitive galvanometer.

Faraday's suggestion was to revolve two discs in the same field, in opposite directions, and then connect the two peripheries together by sliding contacts. The two electromotive forces will then be in the opposite direction in the two discs, but in the same direction with reference to two collecting brushes at the centres of the discs. This will overcome the difficulty, but for more than two discs it becomes impracticable.

Within the last few years a number of unipolar machines have been invented, in which any number of armature wires or bars, may be connected in series with each other, that is, the same field may be used a number of times by repeated inductions in the same circuit. The principle is that the current is led off at the end of one inductor by a sliding contact and by a wire which is fixed with regard to the field, and therefore does not cut lines of force ; this wire is connected to the beginning of

the next inductor by a sliding contact, and so on, connecting them all in series. By this means any desired electromotive force may be induced, while the current may be very great owing to the large and short inductors which may be used.

ALTERNATING CURRENT ARMATURES.

In the general type of alternating current machines the armature consists of a series of coils or turns of wire in one plane, generally placed in a circle at the circumference of a disc which is rotated. On both sides of these coils are a series of fixed field magnets with their opposite poles toward each other thus making a large number of independent fields through which the coils of the armature move when the disc is revolved. The field magnets being so connected that the polarity of each field is in the reverse direction to that preceding, the currents in the armature will be reversed continually as the coils pass through the successive fields. The armature coils are permanently connected with each other, the two terminals of the whole series being connected to two insulated rings on the shaft, on each of which a brush rests for collecting and leading off the current. The armature coils may be with or without iron cores ; in the former case, the induction will be much greater, but the iron heats so much that it is often omitted. All iron cores, even if carefully laminated, will heat if encircled by an alternating current.

Such an armature possesses the great advantage that the coils may be connected in multiple arc, in series, or in any combination of groups, thus permitting the same machine to be readily altered to give a low tension and large current, a high tension and small current, or any intermediate grades that can be obtained by possible groupings of the coils.

The other, and perhaps chief, advantage is that the current is not commutated, and that therefore no commutator is required, thus avoiding all sparking, wearing off of

brushes and commutators. No setting of brushes is required, as there is no neutral line to which they must be set.

A curious feature of some alternating current machines, presumably not in all of them, is that they require more power when running on open circuit than when working with their normal load, and that consequently the machines will get very hot on open circuit. On the other hand when they are short circuited they run light, that is, require very little power to turn them. If an armature coil is to be cut out it should be short circuited and not left open as in constant current machines. The explanation of this is, probably, that the counter induction in the coil is so great when short circuited that it is almost equal to the initial induction, and that, therefore, only the difference between the two will act to generate a small current in the coil.

In the large Gordon alternating current machine the position of the field magnets and the armature is reversed. The field magnets are on the circumference of a large fly-wheel, eight feet in diameter, and are made to move past the armature coils which are fixed to the frame on both sides of the magnets. The great advantage of this is, that the armature coils may be disconnected, short circuited, or grouped in any desired combinations while the machine is running. The coils are generally connected in two groups giving two currents which can be used independently of one another. Regulation may be effected either by varying the field current or by short circuiting some of the armature coils.

In general, alternating current machines must have a separate exciting machine for the field magnets, as these require a constant current; this is, of course, a great objection to their use. In some, however, the current from a few of the coils in the armature, is commutated, so that it becomes a constant current which may then be used for the field.

The great objection to alternating currents, is the

self-induction of solenoids and particularly of magnets. For this reason any shunt solenoids or magnets used in regulators or cut-outs, as in arc lamps, must be made very large in order to have the same power or pull. Any iron used in connection with them must be limited to a small quantity and must be well laminated, or it will heat very much. A core for such a solenoid may be made of a roll of ferrotype iron. The counter electromotive force in a solenoid for alternating currents is not a constant quantity like the resistance, but depends also on the number of alternations, that is, on the speed, and on the current; it will, therefore, vary under any but the perfectly normal conditions, and for this reason, it cannot be depended upon in automatic regulators, meters, and in most measuring instruments, except when coils with very few turns, or in general, series coils, are used, as distinguished from fine wire or shunt coils. Such currents may be measured with an electro-dynamometer, and potentials with some voltmeter without coils, such as the Cardew, which depends on the expansion of a wire heated by the current.

Motors may be run with alternating currents, but it is not advisable nor economical to do so, until their present forms have been greatly improved.

CHAPTER VI.

Calculation of Armatures.

FROM the general principles governing the designing and construction of armatures, which were given in the previous chapter, it will be seen that armatures for generating a definite potential and current may have widely varying dimensions, that is, a number of armatures of entirely different proportions may generate the same potential and current; some one of which will, however, be better than the others. It is not possible, therefore, to lay down a fixed set of rules, by means of which the best proportions of the armature may be determined directly at the outset from the amount of electrical energy to be generated. This must be ascertained by comparing the general calculated proportions of these different armatures with one another, and selecting that one which will be the best under the circumstances. For instance, one armature may have twice as many windings as another, and will, therefore, require half the intensity of field, or half the speed; or it may have half the length, but twice the diameter; or it may have many other combinations of the number of windings, diameter, length, speed, and intensity of field, and yet give the same potential and current. The one which will be the best depends on whether the machine is to be built cheaply, or for the greatest efficiency; whether it may be large and massive, or small and light; or whether the speed may be high, or must be low; in general, it depends on the conditions which limit the construction of the machine. It will, therefore, be different under different circumstances, and must be decided for each case.

It is not necessary, however, to build these different forms in order to find which is the best; it may, in most

cases, be ascertained directly from the calculated dimensions. The best and shortest method for ascertaining these proportions is, therefore, to calculate one form, and then to find by calculation how a variation of each one of the principal proportions will affect the ultimate dimensions and speed; it will then be easy, in most cases, to select from these the one which will be the best under the given conditions. In this selection one should be guided by the calculated efficiency of the different forms, by the general proportions of well-constructed armatures, and by the particular style of frame and armature of the machine.

It is difficult to say what is the best order in which the various parts should be determined. It will make very little difference, however, provided the proportions are afterward varied, to see whether they may be improved. In general, the following order may be recommended for cylinder and Gramme armatures. Assume first a certain induction in volts per foot, which is thought to be attainable in that type of machine. Dividing this into the total number of volts to be generated will give the length of the active wire in one-half. Assume 70 to 80 % of the surface of the armature to be active, that is, embraced by the pole pieces. Dividing the active length of wire by this percentage gives the total length of wire on the cylindrical surface of the armature. From the current which is to flow through the armature determine, approximately, the size of the wire, remembering that the two halves of the winding are in multiple arc, and that, therefore, only half the current flows through each wire. From the length of wire on the cylindrical portion of the armature, and from the diameter of the covered wire, it is easy to ascertain the diameter and length of an armature which will contain this amount of wire on its outside cylindrical surface. The number of layers being always a whole number, which, from the nature of the armature, is limited to very few values, and the circumference of the armature being some multiple of the diameter of the insulated wire, it will generally be found

that two or, at most, three trial calculations will enable one to determine the diameter and length of the armature, and, therefore, those of the core.

For cylindrical armatures, a simple deduction will show that the following relation is approximately correct: the length of the wire, in inches, on the cylindrical surface, multiplied by its diameter in inches (including insulation) and divided by the assumed number of layers, is equal to the cylindrical surface of the armature, in square inches, that is, its length in inches multiplied by its circumference in inches. This will enable one to calculate the cylindrical surface, from which the diameter and length can readily be determined, as the circumference must evidently be such a multiple of the diameter of the insulated wire as, when taken together with the number of layers, gives an even number of lengths, equally divided among the commutator bars or coils.

Another method, which will frequently be found to be shorter, is to assume any fixed number of commutator bars, turns per coil, and layers; this will determine the circumference or diameter of the armature. From the number of wires obtained thus, and from the total length required, the length of the armature may then be readily ascertained. If it is found to be absurdly large or small, it is easy to find what changes in the assumed numbers will correct it.

It is assumed herein that there are no iron or wooden lugs or partitions between the coils on the armature; if, however, such lugs are to be used, the circumference of the armature, obtained as described, must be increased by the sum of the spaces occupied by these lugs; that is, by the width in inches of one lug, multiplied by their number.

After having made these preliminary calculations, it is necessary to ascertain whether the resulting proportions of the armature will comply with other conditions which did not enter into the calculations. For instance, from the

nature of the armature determine the speed at which it will be safe to run it, and from this, together with the diameter, find the inductor velocity. From the induction in volts per foot assumed at the outset, and from this inductor velocity, determine what the intensity of the field must be. This may be ascertained as follows. Suppose the induction assumed was 1.3 volts per foot, and the inductor velocity 45 feet per second, then any one of the wires will move one foot in $\frac{1}{45}$ of a second. A foot of wire generates 1.3 volts, and, as described in the last chapter, it must cut the field at the rate of 130,000,000 lines of force per second, or in $\frac{1}{45}$ of a second it must cut $\frac{1}{45}$ of this, or about 2,880,000 lines of force. As one foot of wire, in moving a distance of one foot, cuts through one square foot of field, the number of lines of force just determined must pass through one square foot, independently of the actual shape or size of the field; dividing this number by 144 gives the number of lines of force per square inch, that is, the intensity of field required to generate an induction of 1.3 volts per foot at a velocity of 45 feet per second. In this case, the intensity of field will be about 20,000 useful lines of force per square inch, which intensity can readily be generated by properly proportioned and economical magnets.

From the diameter and circumference of the armature, ascertain, approximately, what percentage of the length of one complete winding, or coil, will be active, that is, will lie on the cylindrical surface of the armature, taking care to allow for the extra length required at the heads of a cylinder armature, which for short armatures with many windings will be no inconsiderable amount. Dividing the length of wire on the cylindrical surface determined at the outset, by this percentage, gives the total length. From this, together with the size of the wire, find the resistance of the armature, allowing also for the heating. The square of the current, multiplied by the resistance, gives the loss of energy in the armature, which should be from 2 to 10% of the total energy generated by the machine, depending

on its size and on the desired efficiency. If it is found to be much greater, the armature will probably heat badly, being poorly designed for efficiency; if it is less, it shows that a smaller armature could be used, if desired, decreasing some other parts proportionally. A more rational method for determining the diameter of the wire would be to find what its resistance should be from the allowable loss in the armature, and from the current; from this resistance, together with the total length of wire, find its cross-section. But this will frequently be found less convenient, as the length cannot always be ascertained without first assuming some diameter.

Having thus determined roughly the proportions of some one form of armature, which will generate the desired potential, and will not heat too much with the required current, ascertain, by varying such dimension as the nature of the machine will permit, whether the construction of the armature may be cheapened, or whether the efficiency may be increased, or both. As a rule, it is not necessary to make these preliminary calculations with any very great degree of accuracy, as there are a number of factors—such as the self-induction, the heating, the sparking, etc.—which do not enter into the calculation, but which will affect the results. In order to allow for these, as well as for other small errors in calculation, it is advisable to assume a slightly higher potential at the outset. Any small errors made may be corrected in the winding of the field magnets, provided such corrections are not too great to be within the limits of the field.

In series machines the difference of potential at the terminals will be the electromotive force of the armature less the losses in the field coils and in the armature itself. The electromotive force which is used in calculating the armature, should therefore be higher than the difference of potential required by the work to be done, by the amounts lost in the machine itself. The loss in the field magnets may be from two to five per cent. for large well built

machines and up to 10 or 15 per cent. in smaller cheaper ones. The same may be allowed for the armature, though it is advisable to make this loss as small as possible, as the sparking generally decreases with the watts lost in the armature.

For shunt wound machines the electromotive force will be reduced only by that lost in the armature, but the current will have to be increased by the amount passing through the field coils. This may be taken from two to five per cent. for large well built machines, and 10 to 15 per cent. in smaller cheaper ones.

To illustrate the calculation of an armature by this method, assume that a cylindrical armature is to be designed for supplying the current for 150 lamps at 100 volts.

If the lamps require .65 ampere each, the current in the external circuit will have to be $.65 \times 150 = 97.5$ amperes. If the machine is to be shunt wound the current required for the field magnets may be about 3 per cent. of the total current. The armature having to supply both lamps and field will therefore have to generate $97.5 + 3$ per cent. of $97.5 =$ about 100 amperes. As the machine will not be large, the proportion of energy lost in the armature may be taken as about 5 per cent., which will be about 5 volts. As the leads to the lamps will diminish the potential, the machine must generate a higher electromotive force in order that the lamps may have full 100 volts. For this loss in the leads 5 per cent. may be allowed, thus making the potential at the machine 105 volts, and as 5 per cent. was allowed for the loss in the armature itself, the total electromotive force to be generated in the armature must be about $105 + 5 = 110$ volts. The armature, therefore, must generate 100 amperes at 110 volts.

If the armature is to be well-proportioned and has not too many windings or too few commutator bars, an induction of about 1.2 volts per foot may be generated with well-proportioned field magnets and a velocity of the wire

of about 40 feet per second. The 110 volts will therefore require $110 \div 1.2 = 92$ feet of active wire, which must at all times lie between one pole piece and the armature core, that is, must be embraced by one pole piece. As the wire which lies in the neutral part of the field is about 20 to 25 per cent. of the whole amount of wire on the cylindrical surface, the active part is about 80 to 75 per cent. of the whole. Assuming 75 per cent., the whole length of wire on one half of the cylindrical surface will be $92 \div .75 = 123$ feet. As described before, the whole armature wire is, by the nature of the winding, divided into two halves, which are in multiple arc, each half has to generate the full potential of the machine, but carries only half the current. The 123 feet determined as just described from the potential and the volts induced per foot, is therefore the length in one of these halves of the armature wire ; the whole length on the cylindrical surface will have to be twice this, or 246 feet.

The cross-section of the wire should be determined from its allowable resistance, in order that the armature shall not absorb more than about 5 per cent. of the whole energy, but as this would be found to complicate the calculations, it is simpler to assume a certain cross-section per ampere, and after completing the calculations, find whether this will give about the proper resistance, and if not, the proper cross section can then be readily determined. Assuming 520 square mils per ampere, which, for an armature with few layers will not cause it to heat too much, the cross-section of the wire will be $520 \times 50 = 26{,}000$ square mils, as 50 amperes flow through each half of the armature, that is, through each coil or wire. This cross-section is very nearly that of No. 5 B. & S. wire, the diameter of which is 182 mils. The insulation will increase the diameter about 15 mils, thus making the diameter of the covered wire 197 mils.

The length and diameter of the armature might be determined as described from its area, which can be

calculated from the length and diameter of the wire on its cylindrical surface, but it will generally be found to be simpler to determine the diameter and length by trial, as follows: Assume that there are two layers on the armature, and 56 coils or commutator bars; these two assumed proportions may afterwards be varied to find whether any others would be better. Try first three turns per coil; this gives $3 \times 56 = 168$ turns, which, when multiplied by two, gives the total number of lengths or wires lying on the cylindrical surface of the armature, as each turn has two active lengths, one on each side of the armature. This again divided by two, as there are two layers, gives 168, the number of lengths or parallel wires in one layer; multiplying this by the diameter of the covered wire in inches, namely, .197, gives 33.1 inches as the circumference of the inside layer, which is equivalent to a diameter of about $10\frac{1}{2}$ inches.

As there must be 246 feet of wire on the cylindrical surface, made up of 168 turns of two lengths each, there will be $168 \times 2 = 336$ parallel lengths, thus giving $246 \div 336 = .733$ feet, or 8.8 inches, as the length of the armature core and pole piece. This may be checked by calculating the area of the cylindrical portion of the armature, first, from its diameter and length and then from the diameter of the covered wire, the number of parallel wires and their total length. Both should be the same; the area in this armature is 291 square inches.

As this diameter, $10\frac{1}{2}$ inches, is very large for such a small machine, and quite large as compared to its length, 8.8 inches, it is probable that better proportions could be found. Repeating the calculations for two turns per coil and 56 commutator bars gives the following proportions: Diameter, 7 inches; length of core, 13.2 inches. These proportions appear to be much better, as the length is very nearly twice the diameter.

To find how these proportions will satisfy other conditions it is necessary to assume some speed. This must be

based on the mechanical construction of the frame, bearings, and armature. If rigidly supported such an armature may be safely run at 1,200 revolutions. With this speed and a mean circumference of 23.2 inches the inductor velocity will be $23.2 \div 12 + 1,200 \div 60 = 38.8$ feet per second. This is not as high as would be desirable for the best effect and economy, but with such a small diameter a higher velocity cannot be obtained, as it is not advisable to increase the speed. This low inductor velocity indicates that a larger diameter might give better results.

From this inductor velocity and from the assumed induction in volts per foot, determine the required intensity of the field, in order to see that it is not too high. One foot of the wire moves 38.8 feet in one second, and therefore passes through or over an area of $38.8 \times 1 = 38.8$ square feet in one second; in doing so it generates 1.2 volts, as assumed at the outset. From this it follows that it must cut 120,000,000 lines of force in one second, and that these must pass through this area of 38.8 square feet; reducing to inches and dividing gives $120,000,000 \div (38.8 \times 144) = 21,500$ lines of force per square inch, as the required intensity of field, which will induce 1.2 volts per foot at a velocity of 38.8 feet per second. This intensity is not too high and can readily be generated by well-proportioned magnets. If it is found from a similar machine that a greater intensity of field may be obtained economically, the induction in volts per foot may be assumed proportionately higher. For instance, if it is found that 25,000 lines of force per square inch can be generated economically, then the induction may be assumed to be 1.4 volts per foot, as this is in the same proportion to 1.2 as 25,000 is to 21,500, or in other words $25,000 \div 21,500 \times 1.2 = 1.4$. This would decrease the length of the armature in the same proportion, that is, instead of being 13.2 inches, it will be only $1.2 \times 13.2 \div 1.4 = 11.3$ inches, showing the importance of having the field as intense as possible.

To find whether the resistance of the armature is too

high it is necessary to know what the total length of the wire is, including that around the heads. From actual measurement it has been found that an armature whose length is about twice the diameter of core, the wire on the cylindrical or active surface is about 40 per cent of the whole length. The length of wire on the cylindrical surface has already been found to be 246 feet; as this is 40 per cent. of the whole, dividing it by .40 gives about 615 feet for the total length. As the resistance of No. 5 B. & S. wire is .32 ohms. per 1,000 feet, 615 feet will have .1968 ohms, and as the two halves of the whole length are in multiple arc, the resistance of the armature will be one-quarter of this, or .049 ohms. To see whether this resistance will absorb more than the 5 per cent. allowed for it, find how many watts are absorbed by the armature and divide it by the total amount of energy generated. That lost in the armature is equal to the square of the current multiplied by the resistance, or $100 \times 100 \times .049 = 490$ watts. The total amount of energy generated is 100 amperes $\times$ 110 volts $= 11{,}000$ watts. Dividing the first by the second gives about 4.5 per cent., when the armature is cold, but it will still be within the 5 per cent. when warm.

These calculations show that this armature, whose core is about 7 inches in diameter and $13\frac{1}{4}$ inches long, will answer all the conditions and will not be out of proportion. But in order to be assured that no other proportions will give better results, they should be varied, and the corresponding changes made, to see how it will alter the final proportions. For instance, fewer commutator bars, as for example, 48, and say three turns per coil, might give better proportions; there will be $48 \times 3 = 144$ turns, as against 112 in the former case. This would evidently make the diameter larger and shorten the length. A larger diameter enables a greater inductor velocity to be obtained with the same speed of revolution, thus increasing the induction per foot, and thereby decreasing the length of wire. By completing the calculations and making the

deductions as described, it can readily be determined which form would probably be the better.

As it is desirable to increase the diameter of the armature in order to get a greater velocity with the same number of revolutions, the following proportions suggest themselves: Assume 64 coils of two turns of No. 5 B. & S. wire. This gives 128 turns, and a diameter of eight inches. With the same strength of field the induction, 1.2 volts per foot, will therefore be increased in the proportion of 7 to 8, giving 1.4 volts per foot. This, for 110 volts, makes the length of the armature 10 inches. The total length of wire (assuming that only 38 per cent. is active on account of the shorter length) is 550 feet, and the resistance of the armature .044 ohms. This is less than before, showing that with these new proportions less wire will be required, there will be more coils, and as the resistance is less there will be less energy lost in the armature, and therefore less heating; as the heat radiating surface is about the same and the velocity greater, the heating will be reduced still more. The field is the same strength as before. If these new proportions do not affect unfavorably the construction and proportions of the frame, they are evidently better than those first determined.

If it is desired to have only one layer, the following proportions suggest themselves: 56 coils of two turns and but one layer will evidently make the diameter twice as large as before with two layers. This would probably make it too large. The number of coils of two turns must either be taken less, say 48, or it must be greater and have but one turn per coil. 72 coils is probably the largest number practical for such a small machine. The diameter of the wire may evidently be less in this case, as the heat is all generated in one layer. Assuming 72 coils, one turn per coil, and a No. 7 B. & S. wire, gives $7\frac{1}{2}$ inches for the diameter of the armature, and a length of over 20 inches. This is undoubtedly too long to be run safely except with a very stiff shaft.

A No. 6 wire gives 8.15 inches for the diameter, and about 17 inches for the length, the induction being assumed to be 1.4, instead of 1.2, on account of the larger diameter or inductor velocity. The resistance of the armature will be about .049 ohms., which is about the same as that of the first form calculated, which had 56 coils of two turns and two layers. The total length of the wire is about 475 feet, as against 615 feet of larger wire in the other form, showing a great saving of wire.

Numerous other proportions could also be tried; those which are best will depend on the nature of the machine, and must be determined in each case by calculation and by the judgment of the designer.

Particular attention should be given to making the field as strong as possible. In general, an increase in the field increases the induction in the same proportion, and decreases the necessary length of the armature in about the same proportion. This enables the diameter of the wire to be diminished, which in turn makes the whole armature smaller and less expensive.[1]

[1] For the proportions of some well-built machines see Appendix I.

CHAPTER VII.

Field Magnet Frames.

THE general principles underlying the construction and designing of electro-magnets, have been given in chapters iii and iv. As the field magnets of a dynamo usually serve also as a frame work for the machine, their design and construction should be based on mechanical considerations as well as to meet the requirements of good magnets. For instance, it is well known that wrought-iron magnets of the same size as those of cast-iron are more powerful and more economical, but if the nature of the frame of the machine which constitutes these magnets be such as to increase the cost very greatly, it is evident that it will be more economical in such cases to use cast-iron and to make the magnets larger. A cast-iron magnet can in all cases be made to generate as strong and large a field as one of wrought-iron (though not of the same intensity per square inch) by simply making it as much larger as is required by its smaller capacity. The efficiency of the cast-iron magnets, that is, the amount of useful magnetism generated per watt of electrical energy in the coil, may not be as great as the efficiency of wrought-iron magnets, partly because they are not capable of carrying the same number of lines of force per square inch of cross-section, and partly because, being larger in diameter, the wire of the coil has greater length and resistance. But as the amount of energy consumed in the field is, in well built machines, only a small percentage, it would not add very much to the efficiency of the machine to reduce this already small percentage by employing the more efficient and more

expensive wrought-iron magnets. In this, as well as in a number of other points, it is, therefore, a mere matter of choice between first cost as against cost of running, and it may in most cases be determined by the designer either by trial or by approximate calculations.

The general rule regarding the quality of the iron for the field magnets is to have it as pure and as soft as practicable, considering, as just described, both the first cost and the gain in the magnetic qualities. Wrought-iron which has been rolled, usually has a "grain" somewhat similar to that of wood, the fibres running in the direction of the length of the bar. Such iron magnetizes better in the direction of the fibre, than across the grain, and it is therefore preferable, wherever it is possible, to so place the iron that the lines of force run parallel to the grain. Wrought-iron in the form of fine wire or thin sheets may usually be relied upon as being soft, but in this form its use is limited to small machines and to armature cores.

When cast-iron is used it should be as soft and as free from impurities as possible. It is preferable whenever possible, to have it annealed, and when not too large in bulk, to have it converted into malleable iron ; this is especially to be recommended for small machines and motors. Corners, projections, and thin edges should be avoided as much as possible on the castings as they are apt to chill while being cast, thus making them quite hard, and destroying their magnetic qualities. Corners and edges should be well rounded off, and whenever thin projecting edges are necessary for mechanical reasons they should be cast quite thick and massive, and may afterwards be planed or turned down if necessary. It is preferable to cast the iron in dry moulds and to allow it to cool as slowly as possible, preferably for three or four days in a gradually decreasing fire.

The cores of the magnets are usually the parts in which the lines of force are most dense, as it is the smallest cross-section through which the magnetism has to pass. A very

good and economical magnet can therefore be constructed by making these cores of wrought-iron and the pole pieces and yoke pieces of cast-iron.

The relative value of cast and wrought-iron magnets may be deduced from the following figures. Sylvanus Thompson states that cast-iron magnets will give about 60 per cent. of the effect of wrought-iron magnets of equal size. For instance, if a wrought-iron magnet can have 100,000 lines of force passing through every square inch of its cross-section of core, at saturation, a cast-iron one will have 60,000 at saturation ; to be equal to the wrought-iron magnet it would have to be two-thirds again as large in cross-section of core, because every $1\frac{2}{3}$ square inches will then contain the same number of lines of force as one square inch of the wrought-iron core. A wrought-iron magnet, according to this statement, need be only 60 per cent. or three-fifths as large in cross-section as a cast-iron one equal to it in effect. The length of the core will depend in general only on the amount of wire which it is necessary to wind around it in order to generate this magnetic effect in the core.

Kapp[1] states that in two similar machines, differing only in having the field magnets of the one made of cast-iron and of the other of wrought-iron, the electromotive forces generated were 80 and 100 volts respectively. As all other conditions were the same, it follows that the result must be due solely to the magnetism, and that, therefore, the cast-iron has 80 per cent. of the effect of wrought-iron. According to this, a cast-iron core should be one-quarter or 25 per cent. larger in cross-section than an equivalent wrought-iron one, and *vice versa*, a wrought-iron one should be 80 per cent. or four-fifths as large as a cast-iron one.

To determine the actual size of electro-magnets, one should be guided by the following important property of

1. *Electrician*, London, May 22, 1885, p. 23.

such magnets. In passing a current through the coil of an electro-magnet, and varying its strength from 0 amperes to the greatest possible current, it will be found, on measuring the magnetism corresponding to each current, that at first it increases quite rapidly, and very nearly in proportion to the current, that is for double the current there will be about double the magnetism. This will be the case up to a certain point, when the conditions will suddenly change, and on increasing the currents still more the magnetism will increase only very slightly. At this point, called the point of saturation, the action of the iron in adding its share to the magnetism, appears to cease; all the increase above this point appears to be that due to the current itself, as if the magnet were a mere solenoid, or coil without iron. Up to this point the magnetism is obtained cheaply and economically, but above this point the increase in magnetism is so small and requires such a large expenditure of current, electromotive force and wire, that it is prohibitive in well built and efficient machines. It is of very great importance, therefore, to guard against over-saturating to any great extent the magnets or any part of the magnetic circuit of the field magnet frames, as it will always be found that it takes less copper or less electrical energy, to generate the same amount of magnetism in a larger core which is not over-saturated than in a small over-saturated core. This is especially important in small or cheap machines, or in those in which there is a scant allowance of iron in the magnetic circuit. As the actual additional weight of iron required to bring the magnetization of an over-saturated magnet down to the saturation point, is so small, and therefore inexpensive, there is in general no reason why it should not be added. As iron itself appears to add to the lines of force which are due to the current alone, there is an additional advantage in using as much iron as possible, the magnetism of the iron itself requiring very little electrical energy to render it useful. When cast-iron magnets are used there is a still further

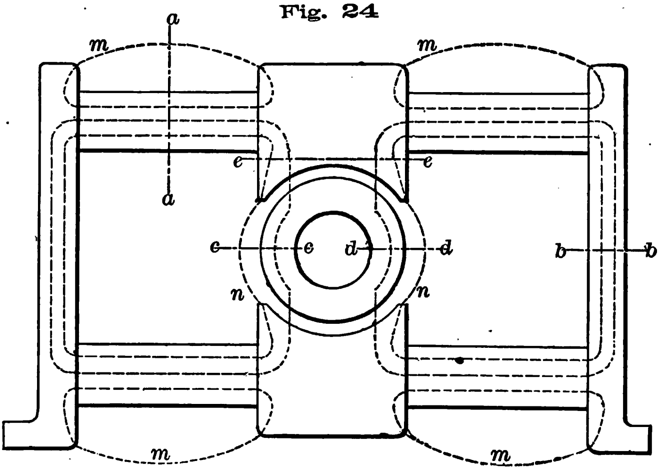
advantage in using larger, massive magnets, as the iron is more apt to be cast soft than when they are small and thin. How to find out whether the magnets are over-saturated too much will be explained in a subsequent chapter. Some makers prefer to over-saturate the magnets to a slight extent because the field is then less sensitive to slight changes of the current in the coils; in other words, the machine is steadier in its action. If this is to be done it should be to a slight extent only. But as machines are generally regulated by altering the current in the field, it would seem that it is desirable to have the field as sensitive to variations of current as possible, in order that it shall require less variation of this adjusting or regulating current.

Scientists have up to the present time failed to give the dynamo builder any practical and reliable data and rules by means of which the actual sizes of the parts of a field magnet frame may be determined with any degree of certainty from the intensity and size of the field required by the armature. In the absence of this greatly needed information, the designer of dynamos will have to use his judgment if he has no access to a finished model machine from which to obtain the desired data. The following relations may be used as a guide in determining the approximate sizes.

Every line of force must make a complete closed circuit around its exciting current, as explained in chapter iii. For instance, in the well-known form of magnet frame shown in figure 24, the lines of force will pass through the iron as shown in dotted lines, the only portion of them which is rendered useful, that is, which may be cut by the armature wire, is that passing from the pole pieces through the air space to the armature and out at the other pole-piece. Iron is saturated when a certain number of lines of force pass through every square inch of its cross-section; if, therefore, the iron was of the same quality throughout, and if these useful lines of force were the only ones, it is

readily seen that the cross-section of the yoke piece at *b b*, should be at least equal to that of the core at *a a*; the cross-section of the pole-piece at *e e*, should be at least twice that at *a a*, as it contains the lines of force from both halves of the frame, as seen from the dotted lines. If a Gramme ring armature is used, the lines of force divide equally, half of them going through each half of the ring; its cross-section *c c* = *d d*, ought, therefore, to be equal to *a a*; if it

Fig. 24



is a cylinder armature the whole cross-section *c c d d* should be equal to twice *a a*. As the lines of force generated in the magnet *a a*, return through the other core below it, it follows that in such a frame each core must be made large enough to contain all the lines of force generated in it and in the other core belonging to that pair, considering them as the two parts of a **U** magnet. In other forms of frames, it may be readily determined what the relative cross sections should be, by merely following the lines of

force throughout their circuit and giving each line of force the same area of iron to pass through. For instance, in the Edison form, one pair of cores take the place of the two pair in figure 24, and should therefore be twice as large in cross-section.

Referring to figure 24, it will be noticed that a few of the lines of force, as *m*, *m*, *n*, *n*, do not pass through the armature and are therefore lost, representing so much leakage, as it might be called. But as these all pass through the cores of the magnets, allowance should be made for them in the cross-section of these cores and they should therefore be larger in comparison to the core of the armature, than if there was no leakage, as was supposed in the above mentioned rule. It is not possible to state just how much to allow for this leakage, as it depends greatly on the detailed parts. For rough calculations it might be estimated that in the forms shown in figure 24, about one-quarter of the total number of lines of force are lost by this leakage, in which case the cross-section at *a a*, should be one-third again as large as that at *c c*.

The iron of the armature is generally of much finer quality than that of the field magnets, and therefore its cross-section per line of force may be made smaller. Taking the results of Kapp's experiments for wrought and cast-iron, given above, it would follow that the cross-section of a wrought-iron armature may be made 80% of that of a corresponding cross-section of a cast-iron magnet core. This would still further increase the cross-section at *a a*, figure 24, over that at *c c*. On the other hand the cross-section of the armature core, which ought to be laminated, is not entirely composed of iron ; allowance should therefore be made for the spaces occupied by the insulating layers, or the air ventilation space.

There is no objection to making the cross sections at any point larger than that which would be required by the rules just given, provided it does not uselessly increase the length of wire on the coils or armature. The important point is

that they should not be smaller than that required by these rules. For instance, the yoke piece at *b b*, or the pole-piece at *e e* may be made as much greater as is desired, the effect will even be advantageous, as it adds to the number of lines of force inherent in the iron. The two places where there should be no more iron than is absolutely necessary are the cross sections of the cores *a a*, and that of the armature *c c*. The latter, however, may be limited by the nature of the armature and its winding, and for cylinder armatures it may often have to be greater than that required by the number of lines of force; in Gramme armatures, on the other hand, it is often much too small for the passage of the required number of lines of force and is therefore saturated long before the field magnets are at their maximum intensity; this causes neutralizing reverse currents in the inside wires, great leakage of otherwise useful lines of force, and consequent bad sparking in the otherwise dead or short circuited coils in the neutral field. The objection to increasing the cross-section of the cores at *a a*, above what is absolutely necessary is, that it increases uselessly the length of the wire of the coils, which in well built machines is an important item in the cost of the material for a machine.

The armature current itself generates quite a number of lines of force in its core. These partly leak through the air and return to the other side of the core, but most of them return through the frame of the field magnets together with the other lines of force, and in the same direction. They therefore help to saturate the iron. If this counter-magnetization of the armature is small, as it should be in well built machines, the effect will not be great; but in armatures with many turns of wire the effect is not small and should be allowed for by an additional increase in the cross-section of the iron.

In the foregoing chapters it was shown how the number of lines of force required by the armature may be calculated approximately. If it were known how many lines

of force could be generated per square inch of cross-section of magnet core for different qualities of iron, and if it were known how many of the lines of force were wasted by leakage, it would be very easy to calculate the necessary cross-section of the field cores. No complete and reliable set of such figures have been published, but the following may serve as a rough guide. Kapp[2] states that in wrought-iron field magnets of hammered scrap, 108,000 lines of force may be passed per square inch of cross-section; in armatures of charcoal-iron, well annealed, 150,000, and of discs of similiar iron, 132,000. Fleming states that in a long magnet of soft annealed iron, the greatest strength is 116,000 lines of force per square inch. The same authority states that in the best dynamo the intensity of magnetization is from about 40,000 to 65,000 lines of force per square inch, by which we suppose he refers to the magnet cores and not to the armature field. In the Edison and Weston machines, tested by the Franklin Institute, a rough estimate gives about 70,000 to 90,000 in the cores.

If a suitable machine of a similar style to the one to be constructed, is at the disposal of the designer, it is very easy to determine from it, as follows, what the cross-section of the cores should be for a larger or smaller machine of the same general type, or of one differing only in the armature. Run the machine with a separate exciter and without a current in the armature; measure the potential on open circuit for gradually increasing exciting currents. When the increase in potential begins to be much slower than the increase in the exciting current the machine is saturated. With this intensity of field at saturation, let the armature current flow through its proper external circuit and measure its current and potential. From this and the detail dimensions of the armature the number of lines of force in the field can be calculated as described

2. Proceedings of Society of Telegraph Engineers, Nov. 11, 1886,—"Characteristics of Dynamos."

in the previous chapters. Knowing the intensity of field required by a new armature for another machine it is only necessary to increase or diminish the cross-section of the magnet cores in the same proportion as the new field is larger or smaller than the one tested.

The length of a magnet core depends only on the amount of wire which is required in its coil to generate the necessary number of lines of force. It is evident that it takes a certain number of ampere turns to develop the required magnetism, and owing to the limited resistance of these coils and to their allowable degree of heating, the amount of wire is also limited. If the coils are very short, the thickness of the coil will be so great that the outside layers may not have their full effect, being too far from the iron; it will also make the outside layers unnecessarily long. On the other hand, if the magnet core is very long, the thickness of the coil will be very small, which by itself is an advantage, but the weight of iron will then be uselessly great, making the machine larger and heavier than is necessary, while the greater magnetic resistance and the greater length of the course of the lines of force will both tend to weaken the magnetic strength and to increase the leakage.

One of the older authorities states that the best relation between the coil and core of a circular magnet is when the core is one-third of the whole external diameter of the magnet, that is, when the thickness or depth of the coil is equal to the diameter of the core. But although this may be the case for telegraph magnets, it is certainly not the case with dynamos, in which the cost of the wire and the resistance of it are of much greater importance than in telegraph magnets. A very good rule, and one which is based on actual experience with machines, as distinguished from theoretical deductions, is to make the thickness or the depth of the coil about one-third of the diameter of the core on round magnets, and one-third of the smaller diameter on oval magnets. If made much

greater than this the magnets will be apt to heat too much, or to over-saturate the core, or to have a uselessly large amount of wire on them. If much less than this, it will generally be found that the magnets are larger than would be necessary to answer the purpose. The latter is no serious fault and will not, as in the other case, prevent the magnets from generating at least the desired amount of magnetism, and on the contrary will allow for an increase of magnetism if it should be found necessary; it is, therefore, much safer to make the cores thicker and longer, and consequently the depth of the coil less, than what might at first appear to be necessary. Furthermore, in many forms of frames, the cores can readily be shortened if it should be found necessary, while they cannot always, so conveniently, be lengthened.

If the number of ampere-turns required for a magnet were known, it would not be difficult to determine the length of the core, because, its cross-section can be determined as described, from which together with the ampere-turns and the allowable thickness of coil, the length is readily calculated. But in most cases the ampere-turns are the last thing to be determined, when the machine is otherwise completed, and it, therefore, remains only for the designer to use his judgment regarding the length which the cores should have. Besides the remarks already made concerning the length of cores, the following may be used as general guides. Deprez states that to have the best effect the length of a magnet should not be greater than three times its thickness; this we presume refers to the core and not to the outside dimensions of the whole magnet with its coil. A short thick magnet will magnetize and demagnetize more readily, or as Fleming states it, "such a magnet has no magnetic memory;" it responds more quickly to changes of current in its coils. Some makers consider this a disadvantage and purposely over-saturate their magnets in order to "steady" them in their action. The tendency of reliable and systematic

dynamo builders has been toward short thick magnets and it may, therefore, be accepted as a safe example to follow.

The following general principles governing the magnetism of coils may also serve as a general guide in designing magnets. In a circular coil of wire composed of a turn or turns of wire, as for instance in a large tangent galvanometer, if the radius in centimeters is r and the ampere-turns are represented by c then the intensity of magnetism at the centre, in lines of force per square centimeter, will be

$$i = \frac{2\pi c}{10r}$$

which may be reduced to

$$i = .6283\frac{c}{r}$$

or if d is the diameter,

$$i = 1.25664\frac{c}{d}$$

Or if R and D are the radius and diameter in inches, and I the intensity in lines of force per square inch, these formulæ become

$$I = 1.5959\frac{c}{R} = 3.1918\frac{c}{D}$$

In these formulæ c will be the current in amperes if there is only one turn in the coil, but if there are many turns c is the current multiplied by the number of turns, that is, the ampere-turns. From these formulæ either the intensity, diameter or ampere-turns may be calculated.

The intensity in different parts of the area enclosed by a circular coil is not the same, being least at the center and greatest nearest the circumference. If the ratio which the mean or average intensity bears to that at the center is known, the total number of lines of force is readily calculated, it

being the average intensity multiplied by the area. On the other hand, if the total number of lines of force enclosed in this circle is known, the mean or average intensity is the total number of lines of force divided by the area.

Expressing this in formulæ, if h is the mean intensity per square centimeter, or H that per square inch, and if k is the ratio of this mean intensity to that at the center, then

$$h=ik$$

and

$$H=Ik$$

If M is the total number of lines of force in the whole circle, then

$$M=ik\,\pi\,r^2=1.9739\ kcr=.98695kcd;$$

or, if the dimensions are in inches,

$$M=5.0137\ kcR=2.5069\ kcD.$$

These formulæ are correct only for a coil in which the cross-section of the coil space is small. For long or thick coils they are not strictly correct, but may serve as a general guide in calculating such coils, and can in general be relied upon for relative proportions between two coils or magnets. For a detailed discussion of this subject the reader is referred to the more advanced scientific treatises.

Numerous deductions can be made from these formulæ, some of which may serve as guides in the construction of magnets. For instance, if the current and the diameter of the coil remain the same, the resistance of the coil does not affect the magnetism which is generated. By increasing the size of the wire of a coil the energy in watts may be reduced to any amount, while the magnetism remains the same; or if the current, and therefore the magnetism, is increased when larger wire is used, so that the number of watts consumed remains the same, then it is evident that the amount of magnetism obtainable per watt of energy may be greatly increased, showing that there is no fixed relation between the amount of magnetism generated and the watts required to generate it, and that theoretically any amount of magnetism may be obtained per watt, it being limited in practice only by the allowable size of the coil space and the cost of the copper.

When iron is introduced into the coil, as in an ordinary electro-magnet, the intensity and total number of lines of force will be increased greatly. The iron acts as if it contained a large amount of magnetism in it, which is rendered active by passing a current of electricity near it. Its action may be pictured as follows: suppose a quantity of steel filings were magnetized very strongly and placed in a round bottle containing thick syrup or any other material which will suspend them but which will not allow them to turn around unless some force is exerted on the particles of steel. Each piece representing an enlarged molecule of iron, being a magnet, will attach itself to others of opposite polarity, thus forming complete little magnetic circuits amongst themselves. If well shaken they will attach themselves as described and will therefore exhibit no definite polarity to a needle placed outside, though they will attract the needle. This represents iron in its normal condition. If a coil be wound around this bottle and a current be passed through it, these little magnets will turn on their axis and arrange themselves perpendicular to the wire of the coil and parallel to the lines of force generated by the current. They will therefore, each add their magnetic intensity to that of the current, as they have arranged themselves in the same direction. They will then exhibit polarity to a needle outside of the bottle, the polarity being the same as that of the coil. The stronger the current the greater will be the force to turn their particles out of their normal position and into that induced by the coil. Their external magnetism will therefore increase with the current until they have all been turned parallel to each other, when the increase of magnetism of the particles will stop. This corresponds to the point of saturation above which the magnetism of the iron itself cannot be increased. When the current is stopped they will again attach themselves to each other forming closed magnetic circuits, and not showing any external magnetism.

The application of the formulæ just given may be

illustrated as follows: Suppose the magnets of a dynamo which has been tested, were found to be over-saturated too much, and it is desired to construct a new frame for this machine in which they were not to be over-saturated. By the tests which will be described in a subsequent chapter, find what the magnetism must be for the proper load of the machine when the magnets are over-saturated; call this m. It is not necessary to know the actual number of lines of force but merely a number which is proportional to it, such for instance, as the potential in volts measured on open circuit, with the magnets excited to the required degree of magnetization. Make another test to determine the magnetism in the magnets (or the potential on open circuit) when they are just saturated; call this n, and let the number of ampere-turns required in this case be c. From n and the area of cross-section of the core, find, by dividing the former by the latter, what the intensity of magnetization per square inch is, just at saturation. If the number of volts has been used instead of the number of lines of force, the number thus obtained for the intensity, will by itself mean nothing, but it will nevertheless, be proportional to the intensity per square inch, and can be used in the further calculations. This intensity is what may be allowed in the new magnets. Dividing the required magnetism m by this allowable intensity, will give the area of cross-section which the new magnets must have in order not to be over-saturated, the quality of the iron being supposed to be the same. From this new area find the diameter, and call it D_1, the old diameter being indicated by D. It then remains to find what the new ampere-turns must be in order to develop this intensity. From the formula for the value of I it is evident that if the intensities in two cases are the same the ratios of the ampere-turns (c) to the diameter will be the same in the two cases, that is,

$$\frac{c}{D} = \frac{c_1}{D_1}$$

in which c_1 represents the ampere-turns required for the

new magnets. As the ampere-turns c of the old magnets when just saturated, and the old and new diameters D and D_1 are known, the value of the new ampere-turns c_1 is readily determined ; it will be

$$c_1 = \frac{c}{D} D_1.$$

Owing to some small errors which are involved, these calculations will not be exact, but they will serve very well as a guide.

From this new number of ampere-turns and from the dimensions of the old magnets, it can readily be calculated whether the new magnets must be made longer, or whether they may be still shorter. To illustrate this, suppose the old magnets showed no signs of heating when they were being run just at saturation, developing the magnetism which was indicated by n. This would show either that more electrical energy may be used for the magnet coils (*i. e.* for a shunt machine thicker wire could be used, or for a series machine thinner wire), or that the heat radiating or external surface of the whole coil (not of the wire itself) may be smaller, and as the diameter of the coil is larger it shows that the length of the coil could be less. Knowing the periphery of the core, the size of the wire, and the number of ampere-turns, and assuming a certain thickness or depth of coil, the length of core necessary to contain this wire can readily be calculated This subject of the winding of magnets and length of core will be further discussed in the next chapter.

The types of field magnet frames now in common use and having only two active poles, may be divided into the four following general classes, shown in figures 25, 26, 27, and 28, in which the coils are marked m. They are classified here with reference to the relative position of the magnets proper, their pole pieces and their yoke pieces. Any other modifications of these general types are considered as details which do not effect the general classification.

The form shown in figure 25, consisting of a single **U**

magnet with two coils, is probably the oldest type. It was used in the old machines of Wilde and Pacinotti. It is the form used at present in the Edison, Hopkinson and Jurgensen machines, and when the yoke piece is also

Fig. 25

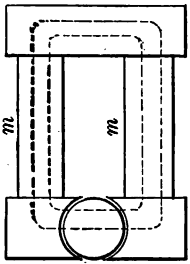


Fig. 26

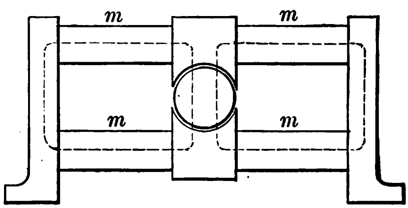


Fig. 27

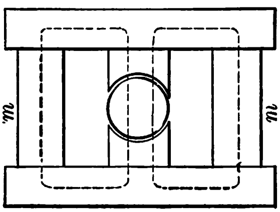
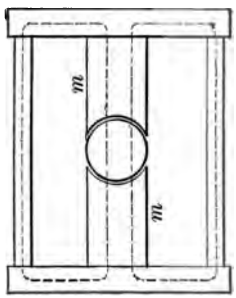


Fig. 28



covered by the coils it is the form used in the Sir Wm. Thompson and the Mather machines. For the same amount of magnetism in the armature field, the only advantage in covering the yoke piece with coils, is a slight saving of iron and of wire, as it is evidently a more economic dis-

position of the wire and iron, but it is accompanied by increased difficulties in winding. The type shown in figure 25, is better adapted for Gramme ring armatures than for cylinder armatures, as the field is not always perfectly balanced, being stronger on that side of the armature nearest the yoke piece. The difference may, however, be made very slight.

The more common type, shown in figure 26, consists of two **U** magnets with their like poles together. For the same magnetism in the armature, the cores and yoke pieces need be only about half as large in cross-section, as they would have to be in figure 25, as the lines of force, shown in dotted lines, divide evenly between the two **U** magnets. The quantity of wire being approximately the same, the length of the cores could be made somewhat shorter than in the type shown in figure 25, thus shortening the path of the lines of force and therefore the magnetic resistance offered by the iron. As it is desirable to have this magnetic resistance as small as possible, this feature of shorter circuits is an advantageous one. The field may evidently be perfectly balanced. This type is the most common, being used in the old and new Gramme machines, the Weston, Brush, Siemens, Maxim, Burgin, Crompton, Patterson-Cooper, Kapp, Jenney, Western Electric, Daft, Ball, Schuyler, Clark, Wood, Heinrichs, Knowles, Westinghouse, Consolidated Company, and no doubt numerous others. When the yoke pieces are likewise covered with coils, this type includes the Ewell-Parker frame.

The type shown in figure 27 is closely allied to this one, the two coils of each **U** magnet being combined together into one, and placed on what is the yoke piece in figure 26. Comparing it with figure 25, it will be seen that the lines of force generated by one coil in figure 27, do not have to pass through the other coil, as they do in figure 25, and therefore the cores can be made smaller, each coil saturates only its own core and not that of the other coil. If this

were the only thing to be taken into consideration, the cores in figure 27 need be only half as large in cross-section as those in figure 25. The length of wire required will, however, affect this dimension on account of the limited length of the cores which, in this type is dependent on the size of the armature and other dimensions. Comparing it with figure 26, it has the advantage of having only two coils instead of four smaller ones. The circuit of the lines of force and therefore the magnetic resistance, may also in many cases be made smaller in figure 27 than in figure 26 ; there would probably also be a saving of iron. The objection to this form is, that, unless the distance from the pole-piece to the coils is quite large, many of the lines of force will leak directly back into the cores, and as these do not pass through the armature they are wasted. This type is used in the McTighe, Hopkinson, Griscom, and Joel machines.

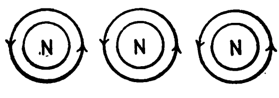
The type shown in figure 28 may also be considered as two **U** magnets shaped like the path of the lines of force, as shown, with the coils around their common pole pieces. It has the same advantage in having only two coils, but unlike figure 27 they saturate each other's cores, as in figure 25. It generally has the disadvantage of having a very long circuit for the lines of force, it being considerably over four times the length of a coil ; this, however, is partially overcome by the fact that the coils may be made thicker and, therefore, shorter in this type than in the others. It is like figure 26 and 27 and unlike figure 25, in the feature that the field may be perfectly balanced. It is like figures 27 in the fact that there generally is great leakage of the lines of force from the pole pieces to the yoke pieces. Among the machines using this type are the Thomson-Houston, Van Depoele, Hochhausen, Kapp, and in general most multi-polar machines, as for instance, alternating current machines of the ordinary types.

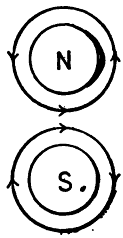
In some of the older forms of machines several small

parallel magnets with common pole and yoke pieces were used in place of one larger magnet. The best known machines of this kind are the Edison "Jumbo" and the older Weston machines. Such magnets were, however, soon abandoned by the makers. They take up much more space and require a much larger amount of wire, the wire on those parts of parallel coils which face each other, being disposed so as to neutralize the magnetic effect of those parts. This may be seen from figure 29 in which three such magnets are shown in cross-section; the current flowing around them as shown, it will be seen that the parts of the coils nearest each other tend to neutralize one an-

Fig. 30

Fig. 29





other, as the neighboring currents are in the opposite direction, thereby destroying their magnetic effect. These portions of the wire are, therefore, inactive magnetically, being mere dead resistance. In such a composite magnet it can readily be shown that there are lines of force between the magnets running parallel to them, but in the opposite direction to the useful lines in the magnet cores. These are, of course, wasted, as they do not pass through the armature.

It is often supposed that two parallel magnets forming one **U** magnet as in figures 25 and 26, are subject to this same objection, and that, therefore, the coils should not be too near together. But this is not the case, it is on the

contrary an advantage to bring them as near together as the nature of the frame will permit. This will be seen from figure 30, which shows the cross-section, perpendicular to the cores, of the two parts of one **U** magnet in figure 25 or 26. It will be seen that the currents in two neighboring wires of the two coils must be in the same direction, in order to develop the two opposite poles at the ends of the magnets. The currents in the upper half of the lower coil are, therefore, in the right direction to act with those in the upper coil to saturate the core N, and *vice versa.* In other words, each coil tends to saturate the core of the other coil, as described in another part of this chapter. It is, therefore, an advantage to bring such magnets quite close together, provided they are not so near as to allow the lines of force to leak directly from one to the other near the pole ends.

The shape of the pole pieces around the armature has already been discussed in the chapter on armatures. The air space between the pole pieces and the armature core should be made as large as possible in area, and as thin as practicable. It is not the case, as is sometimes claimed, that according to the law of inverse squares, the intensity of this field will be inversely as the square of the distance between the iron. That is a misinterpretation of the law. The field does become weaker as this thickness increases, but as Deprez has shown, this decrease in strength is much smaller than is generally supposed.

As described before, the pole-piece projections should not be too near to each other, and they should not be too near to any other iron parts on account of leakage. They should be rounded off on their outside edge to avoid the tendency to leakage from the sharp edges. It should be remembered that these projections are often the most intense parts of the field. It is probably an advantage to incline the edges of these projections instead of making them parallel to the axis, in order to cause the wire to enter the field gradually instead of suddenly.

For cylinder armatures, it is important to have the field well balanced magnetically, that is, to give it the same intensity per square inch throughout, or else to have it symmetrical with respect to the axis, on both poles. This is not so important for Gramme armatures, but it is essential for these and for most cylinder armatures to have the same number of lines of force in both pole pieces, and to have the wires cut them at the same speed, otherwise there may be local currents in the armature as described before. It is, therefore, necessary to avoid unsymmetrical leakage, as for instance, from one pole-piece through half the armature, and returning through the shaft and the single iron bearing support, back to the magnets; such lines are cut by only one side of the armature.

Accessory iron parts of the frame or base plates, should be as far removed from the pole pieces as possible, to avoid leakage. For the same reason braces or bearing supports should not be fastened to pole pieces, or else should be made of brass. If for convenience they are of iron and are fastened to the pole pieces, they should be symmetrical and be separated as far as possible from each other.

CHAPTER VIII.

Field Magnet Coils.

ALTHOUGH methods have been suggested for calculating directly the size of the wire and the number of turns in field magnet coils, from the magnetism required, yet until such methods have stood the severe test of repeated application in practice, they must be regarded merely as suggestions which may or may not be more trustworthy than the methods already in use. It can hardly be expected that any new methods based on calculations only, will ever prove to be more reliable and sure than the well tested method to be described, which is based on the actual performance of the machine.

There are a number of factors which enter into such calculations, which are either unknown or uncertain, and which will, therefore, make the results less reliable. Until these quantities are known any determination of the coils based merely on calculations without testing the machine, will be approximate only. Among these uncertain or unknown quantities are the magnetic qualities of the particular iron used, the effect of the shape of the magnetic parts, the air space in the magnetic circuit, the magnetic leakage, the resistance equivalent of the self-induction of the armature and field magnet coils, the effect of the number of pulsations or of armature coils, the Foucault currents in the armature coils and in the pole pieces, the counter magnetism in the armature commonly called the magnetic lag. It is known, however, that under certain conditions, easily obtainable in practice, the effect of a number of these quantities or proportions is so small that it may be neglected. The effects of some may be eliminated by taking as a basis of the calculations the known results of a similar machine

of the same general type and proportions, though not necessarily of the same actual size. Recent investigations[1] in apparently the right direction, may however lead to the determination of certain reliable constants and relations which will materially aid the engineer in calculating more definitely the relations between the exciting coils and the field, without first constructing a number of trial machines.

As described before, it is the electromotive-force which the machine generates and maintains, the current being dependent only on this and on the total resistance in circuit. This electromotive-force depends on the armature, on its speed and on the magnetism, which latter depends on the iron parts and on the ampere-turns. Therefore, if the armature and frame have been constructed as described, and the safe speed determined upon, the only other factor which remains undetermined and which may be made to correct any small errors or inaccuracies in the determination of the armature and frame, is the winding of the coils.

This may be determined with all due accuracy by the following method : When the machine is completed in all its parts except its coils, erect it and place on the magnet cores temporary coils of a known number of turns. These coils should all have the same number of turns ; the size of the wire will depend on the electromotive-force and current of the separate exciting machine or battery which must be used to supply them with current ; it should be large if the exciter gives a strong current of low electromotive-force, and small if it gives a small current of high electromotive-force. They may be wound on shells of brass or ordinary tinned iron, and should have a depth of winding about equal to that which the final coils should have, in order that the inaccuracies due to different thicknesses of coils may be eliminated.

The machine is then run at its proper speed as a separately excited machine, the current for the coils being sup-

1. Proceedings of the Society of Telegraph Engineers, November 11, 1886. Kapp on characteristics of dynamos.

plied by a separate dynamo or by a storage battery, which must be so arranged with adjustable resistances or other regulating devices, that the current in the coils may be varied at will. The current from the machine is discharged into a large rheostat, or in the absence of such a resistance it may be sent into a battery of storage cells or into a circuit of incandescent or arc lamps, though the latter is not to be recommended, as the arc lamps make the current too unsteady. The exciting current is then varied and adjusted until the machine gives its proper potential when the current has the required strength, the brushes having first been set to the proper position to avoid sparking. When all the adjustments have been made and the current and potential measured to see that they have their desired values, the current which flows through the exciting coils should be measured as accurately as possible. This exciting current is then multiplied by the total number of turns in the temporary field coils, which gives the number of ampere-turns that are required to excite the magnets of the machine while it is generating its proper potential and delivering the proper current. From this number of ampere-turns the proper size of the wire and number of turns for the new coils of the machine can readily be determined, as will be described. The magnetism of a core depending only on the ampere-turns, it is immaterial whether these are generated by many windings with a small current as in shunt machines, or by few windings with a strong current as in series machines, or by a combination of both as in compound machines ; all that is necessary is that the sum of the products of the current and number of turns of wire remains the same.

The following precautions should be taken in making this preliminary test for determining the ampere-turns :— The temporary coils of the machine when separately excited should be connected in series with one another, for if they are in multiple arc an error may arise from a possible unequal distribution of the exciting current in the different

coils due to different resistances. In the absence of an exciting machine or battery the temporary coils may be supplied with current from the machine which is being tested; they may then be wound with tolerably fine wire and have an adjustable resistance in series with them, the connections being made like those for a shunt machine, the shunted current being added to the main current as part of it. Or the temporary coils may be wound with coarse wire and connected as in a series machine, the adjustable resistance being in that case connected as a shunt to the coils, and the potential of the machine being measured at the brushes and not at the poles, as some of the potential is used in the coils.

If the finished machine is to be a series wound machine a portion of the potential of the armature is consumed in sending the current through the magnets. This may be as low as 1.5 or 2% of the whole potential in large well built machines, and as high as from 15 to 20% in smaller cheaper machines; it represents the percentage of energy required in the magnets. In the preliminary test for determining the ampere-turns this should be taken into account, the exciting current being increased until the potential of the machine is that which will be required for the magnets in addition to that required for the external circuit. If the finished machine is to be shunt wound, a fractional part of the whole current generated will be required for the magnets; this varies from 1.5 to 2% of the whole current in large well built machines, and is as high as 15 to 20% in small or cheap machines. In the test for the ampere-turns the machine should therefore be excited until the current is equal to the sums of the main current and this shunted current. In compound machines both of these corrections should be made, the whole percentage of energy being divided between the two sets of coils according to their functions. For instance if 3% be allowed for the magnets, $\frac{1}{3}$ of this or 1% of the potential might be allowed for the series coils, and $\frac{2}{3}$ or 2% of the current for the shunt coils.

The magnets should not be over-saturated except when

it is desired to "steady" the current by having the magnets less sensitive to changes of current in their coils. This applies, of course, only to self-excited machines; in those in which the magnets are separately excited, as in some central station plants, or as in most alternating current machines, there is apparently no reason for over-saturation. Well built compound machines should never be over-saturated, nor even too near the point at which saturation appears to be complete, as it is then difficult, if at all possible, to wind them compound for a constant potential. How to determine, before winding the magnets, whether they are over-saturated by the required magnetism, will be set forth in a subsequent chapter on examining machines.

SEPARATELY EXCITED MACHINES.

If the finished machine is intended to have its magnets energized by the current from a separate machine the calculation of its winding becomes very simple. Suppose the preliminary test with temporary coils, just described, showed that 20 amperes were required, and that there were 250 turns or windings on each coil, the type of magnet frame being that shown in figure 26, chapter VII., in which there are four coils; there will then be $4 \times 250 = 1{,}000$ turns, which with 20 amperes gives a total of 20,000 ampere-turns as a measure of the magnetism required. The number of ampere-turns or ampere-windings thus determined will hereafter be represented by $(a\,W)$.

To determine the winding for the finished machine assume any suitable current and divide this number of ampere-turns by it; this will give the required number of windings or turns of wire, which again divided by the number of coils gives the windings per coil. Any suitably sized wire may then be chosen, which when wound to the required number of turns will not make the coil too large, a good practical guide for which is to make the depth of the coil about $\frac{1}{8}$ the diameter of the core when round, or $\frac{1}{8}$ of the lesser diameter when oval. A more direct method

of finding the proper size of the wire is to divide the area of cross-section of the coil space in square inches (that is the length of the coil multiplied by the depth or thickness) by the number of turns of that coil; this will give approximately the space for each wire, the square root of which is the diameter of the insulated wire in inches.

The current for such magnets should be chosen with reference to the cost of the wire for the coils, the cost of winding it, and the length of the leads from the exciting machine. Considering the cost of the wire only, the current should evidently be as strong as possible and the potential correspondingly low, in order to increase the size of the wire as much as possible, as coarse wire is cheaper per pound than fine wire, and it may be assumed that the weight of coils having the same cross-section of coil space is nearly the same whether coarse or fine wire is used. Considering the cost of winding, however, a limit is soon reached. Although it costs less to wind fewer turns of coarser wire than many turns of fine wire, the cost again increases when the wire becomes so thick as to be unmanageable. Considering both of these factors the wire should be chosen as large as it is easy and cheap to wind. If the exciter is at a great distance from the machine the additional cost of the leads, for a strong current, may necessitate taking a smaller current, and, therefore, more turns of finer wire on the magnets; but this case would probably occur seldom, if ever, as the exciting machine is generally near the other.

In some cases it may be preferable to reverse this method and to determine first the largest wire which it is practicable to use, then find how many turns can be wound into the given coil space, and finally by dividing this number of windings into the number of ampere-turns per coil, find what the current must be.

The case may occur when the magnets must be wound to suit a certain exciter giving a definite current and electromotive force. The current for the magnets being fixed, the number of windings are determined by dividing it into

the ampere-turns $(a W)$. The size of the wire must then be chosen so that when wound to the required number of turns its resistance is such that the potential required is within the limits of the capacity of the exciter. In other words, if C and E are the available current and potential of the exciter, the resistance of the coils must not be greater than $R = \frac{E}{C}$. On account of the self-induction of the coils, the heating, a possible slight error in the diameter of the wire, or other factors increasing the apparent resistance, it should not be as large as $\frac{E}{C}$, but should contain a "factor of safety" by making it, say 15 to 20% less.

The size of the wire could be determined by trial by calculating the resistance of the required number of turns with different sized wires, but the following method will be found to be more direct.

Let d, represent the diameter of the bare wire in mils or thousandths of an inch ;

l_m, the average length of one turn in inches ;

R, the resistance of all the magnet coils in legal ohms ;

W, the total number of turns on the magnet coils of the finished machine ;

a, the current in amperes in the magnet coils of the finished machine ;

$(a W)$, the ampere-turns obtained from the preliminary test ;

θ, the specific resistance (metric) at the allowable temperature of the coils.

The resistance of the finished coils will then be

$$R = 50.13 \frac{W l_m \theta}{d^2}$$

and according to Ohm's law,

$$R = \frac{v}{a}$$

in which v is the potential in volts which is consumed in the coils. Hence it follows that

$$d = \sqrt{\frac{50.13\ (a\,W)\ l_m\ \theta}{v}}$$

or assuming θ equal to .0162 and the temperature about 70° F,

$$d = \sqrt{\frac{.875\ (a\,W)\ l_m}{v}}$$

in which it is necessary merely to substitute the particular values, and reduce it, to find the diameter directly. v should in this case be 15 to 20% less than that which the exciter will give, in order to include the factor of safety above referred to.

In order to calculate the diameter of the wire by this method, it is necessary to know the mean length of one winding of a magnet coil. But this is itself dependent upon the size of the finished coil which however is not yet known. A formula might, therefore, be deduced which should give the diameter of the wire directly without first knowing the length of a winding, but it has been found that such a formula is too complicated to be of much use to the practical builder of dynamos. In place of such a complex formula the following approximate method will be found to answer equally well, and to be much simpler in most cases.

If the depth of winding, or thickness of a coil, be too great, the proportions of the machine will not be the best, as the outside layers will be very long and far removed from the iron, and although the economy in the iron might be great yet the more important economy in copper will be poor, and the iron will probably be over-saturated. On

the other hand if the depth of winding is too small, the economy of iron will be poor, that is, the magnets will be longer and therefore heavier than is necessary, while the economy of copper will be good. There must, therefore, be a certain depth at which the economy as a whole, considering both the iron and the copper, is best. Until more extended experiments have been made to determine more accurately the best proportions, it will be found to give fair results to make the depth of winding about one-third of the diameter of the core, if round, and one-third of the lesser diameter, if oval.

In order to find the mean length of one winding, it will be sufficiently accurate for all practical purposes to assume a depth of winding as described, and from this, together with the dimensions of the cross-section of the core, to calculate the mean length of a turn. If the thickness of the finished coil should then be found to be slightly different from that assumed, it will make very little difference in the mean length, for in an actual case it was found that diminishing the depth as much as 50 per cent. decreased the mean length of one turn only seven per cent.

For an oval coil not too flat the lengths of the inside and outside layers are in the proportion

$$\frac{a + b}{a + b + 4\,c}$$

in which a and b are the length and breadth of the cross-section of the core and c, the assumed depth of winding. From this the mean length of a turn in inches will be

$$l_m = l + \frac{2\,c\,l}{a + b}$$

in which l is the periphery of the core or the length of one turn of the lowest layer, all dimensions being in inches. For a circular coil the diameter of whose core is D, the mean length of a turn will be

$$l_m = \pi\,(D + c)$$

which, if c is one-third of D, becomes

$$l_m = \tfrac{4}{3}\,\pi\,D = 4.189\,D$$

Having thus found the mean length of a turn, there remains only to substitute its value in the above formula for d, in order to calculate the diameter of the bare wire, which when wound to the proper number of turns will have such a resistance as will enable the proper current to flow through the coils when the exciter has the potential stated at the outset. There is one condition however, which must be fulfilled, namely that the actual depth of winding should not exceed too much that which was assumed, as the resistance may otherwise be too great. In general, if the actual depth of winding is found to differ greatly from that which has been assumed it shows that the magnets are not proportioned as well as they might be. It is necessary, therefore, to check the results obtained, and at the same time to see whether the magnet cores are properly proportioned, by proceeding as follows. Having calculated the diameter of the bare wire, as described, find what the outside diameter of the insulated wire is, which may be done by winding closely ten turns around a mandrel, and measuring the length of this small coil in inches and decimals, which when multiplied by 100, will give the outside diameter of the insulated wire in mils; let this be represented by d_1. Dividing this into the length of a core in inches multiplied by 1,000 to reduce it to mils, will give the number of turns per layer, and this divided into the number of turns per coil found at the outset, will give the number of layers, from which the depth of winding is readily found, as it may be taken approximately equal to the number of layers multiplied by d_1 in mils, and divided by 1,000 to reduce it to inches.

If this is found to be about the same depth of winding as that which was assumed at the outset, the core and coils are probably well proportioned, provided other points such as the heating of the wire and the over-saturation of the

core have been guarded against. If this actual depth is much greater than that assumed, it shows that the cores or coil spaces are probably too short, and should be lengthened to such an extent that when the same number of turns are wound around the new core, the depth of the coil will not exceed about one-third of the lesser diameter of the core. If this actual depth is only slightly greater than that assumed, it may not be necessary to lengthen the cores of that particular machine, though it is advisable to make the change on the pattern if it is to be used for other machines; in case it is not changed for that particular machine, it is advisable to make a new calculation for the depth and the mean length of a winding found from the first calculation.

If, on the other hand, the actual depth is found from the calculations to be less than that assumed, the machine may be finished without any alterations in the size of the core; but, as the core in this case is longer than it needs to be, it would be better for the sake of economy of iron, to shorten the cores so that the same number of turns on the shorter core would make the thickness or depth of winding about that which was assumed; the machine would otherwise be uselessly heavy.

It is assumed in these cases that the magnet frames are not over-saturated more than is desired, and that the coils do not heat too much In order to guard against over-saturation, it is preferable first to make the test for saturation, which will be described in a subsequent chapter, in order to find what the allowable number of ampere-turns is in case the magnet frame is over-saturated, or the cores improperly proportioned. This test gives the greatest number of ampere-turns which should be used on that machine. If the number of ampere-turns which are required to generate in the armature the required potential and current be found to exceed this limit, it shows that some or all of the iron parts of the machine are too small for the required magnetism, and that, if the machine is to be properly proportioned, the cross-section of the iron parts, measured per-

pendicularly to the lines of force, should be increased by a certain definite amount which can be calculated as described in chapter vii. If the iron is not over-saturated to a great extent, it may be possible to finish the machine without altering the size of the iron parts, by increasing the depth of winding or the amount of current or potential allotted to the coils, or both, but the machine will then evidently not have the best proportions. If, on the other hand, the number of ampere-turns, which are required to generate in the armature the required potential and current, be found to be much less than the limit obtained from the saturation test, no alterations in the size of the iron parts are necessary, but as this shows that there is more iron than is essential to produce the required results, the machine is uselessly large and heavy, and therefore has not the best proportions. It would be preferable to reduce the cross-section of the iron parts, as described in chapter vii., in order that they may be just at the point of saturation, or slightly above it, if desired, for the sake of steadiness of current.

To guard against heating, the following general rules may serve as a guide: In large magnet coils the current density in the wire may be about .001 to .0015 amperes per square mil or .00079 to .0012 per circular mil[1] of cross-section of the bare wire, which is equal to about 1000 to 1500 amperes per square inch, or 1000 to 650 square mils per ampere, or 1300 to 850 circular mils per ampere. In magnet coils made of fine wire, as in shunt machines, the current density in amperes per square mil may be slightly higher than in coils of coarse wire, as in series machines. The size of the wire should, therefore, also be determined from the current in order to guard against heating, besides being calculated from the formula first given, in which it depends on the allowable resistance. Should these two values for the diameter differ, the larger of the two will have to be taken in order that both the resistance and the heating will not exceed the limits.

1. A circular mil is the area of a circle whose diameter is one mil.

But a rule of this kind in which the current is limited only by the cross-section of the wire, although very simple in its application, is not sufficiently general to be relied upon in all cases. While it will give fair results for similarly proportioned coils, not differing too much in the actual sizes, it is less reliable for coils whose proportions and dimensions differ very considerably from those from which the constants were taken, which were ordinary oval machine magnets, not too long, having a moderate depth of winding, and which were exposed to the air on all sides. A much more reliable rule, though less convenient and not always as simple in its application, is based on the following considerations: The heat in a coil is developed by the watts or volt-amperes which are consumed in the coil itself; this is a constant and continuous supply of heat which would continue to accumulate and ultimately destroy the coil if it were not continually dissipated from the outside surface of the coil as well as from the outside surface of the iron parts in the immediate neighborhood of the coil. The dissipation of the heat will depend on the temperature and on this exposed or outside surface, which for simplicity in calculations will be limited here to that of the coil alone. The coil will therefore increase in temperature until the heat dissipated is equal to that generated in it. In calculating a coil to guard it against heating too much, it is therefore better to consider only these two factors, namely, the watts consumed in the coil and the outside surface of the coil. The density of the current in the wire, or, in other words, the cross-section of the wire as compared to the current, may be neglected entirely, for it is evident that if the outside surface of the coil, and the number of watts consumed, be the same in any two coils, the heating will be the same no matter what the current per square inch is. For instance, suppose two magnet coils are wound so as to have the same external dimensions, one having two layers and the other one layer of the same sized wire; the resistance of the former will

be about twice that of the latter. Now if the current is 10 amperes in the first case and 14 amperes in the second, the energy in watts will be about the same in both cases, and as the external cooling surface is also the same, the heating will be the same, notwithstanding that the current density is very much greater in the second case than in the first. The same result might be shown with coils of unequal sizes and shapes, having different depths of winding. In general, the current density may be greater the less the depth of winding or number of layers.

In an article by Prof. George Forbes,[1] he deduces the following general laws regarding the heating of coils: In coils of the same size but wound with wires of different diameters, so as to occupy the same volume, the current must vary as the cross-section of the wire, in order that they attain the same temperature. In other words, in such coils the current density in the two wires must be the same. Another deduction is, that in two coils of similar shape (the linear dimensions and the diameter of wire of the one being n times that of the other), the squares of the currents will be proportional to the cubes of the linear dimensions when the heating is the same. In other words, if one coil is twice as large in all linear dimensions as another, and has wire of twice the diameter, the square of the current in the larger one may be made $2^3 = 8$ times as great as the square of the current in the smaller; that is, the current in the larger may be $\sqrt{8} = 2.8$ times that in the smaller, in order that both attain the same temperature.

In the same article he gives a formula which he states agrees with what is actually found in practice. From this formula the following practical rules may be deduced: A watt of electrical energy will be dissipated for every 800 square centimeters of external surface of the coil, when the temperature of the coil is 1° centigrade

1. Proceedings of the Society of Telegraph Engineers and Electricians, March 24, 1884.

higher than that of the air; reducing this to our ordinary units, it is 223 square inches for 1° Fahrenheit. The number of watts which can be dissipated from a given surface of coil increases directly with the temperature which the coil may have above that of the atmosphere; that is, for double the increase in temperature the watts in the coil may be twice as great; or for the same allowable temperature, it increases directly as the surface of the coil is increased. The same rules may also be stated as follows: The rise of temperature above that of the atmosphere will be 1° centigrade for every watt and every 800 square centimeters of surface; or 1° Fahrenheit for every watt and every 223 square inches of surface. For the same surface it increases as the number of watts, or for the same watts it increases as the surface decreases. Every square centimeter will dissipate a watt at 800° C. above the atmoshere, and every square inch will dissipate a watt at 223° F. above the atmosphere. The surface must increase with the watts or decrease as the allowable temperature increases.

All these rules may be expressed by the formula,

$$w = \frac{1}{800}\ t\ s$$

in which w is the number of watts lost in the coil; t is the temperature in centigrade degrees *above* that of the air; s is the outside surface of the coil in square centimeters.

In the other units it will be

$$w = \frac{1}{223}\ T\ S = .004476\ T\ S$$

in which T is in Fahrenheit degrees, and S in square inches.

In place of the number of watts, w, may be substituted

the equivalents $C\ E$, $C^2\ R$, or $\frac{E^2}{R}$, in which C, E and R represent the current, electromotive force and resistance, respectively, of the coil, the resistance being that at the temperature to which the coil may be raised. For instance, substituting $C\ E$ for w and reducing, gives

$$C = \frac{T\ S}{223\ E}$$

which gives directly the greatest current which can be used in the magnet coils of a shunt machine having a certain potential, in order that they do not heat above an allowable temperature; this current can therefore be calculated even before the winding has been determined, as it is independent of the number of turns or the resistance, if only the size of the external surface is known approximately; this maximum current should never be exceeded.

Numerous other useful formulæ can be deduced in the same way. For instance, if a maximum rise of temperature of 80° F. above that of the air is allowed for the magnets, the greatest allowable current will be

$$C = .36\ \frac{S}{E},$$

or if the resistance instead of the electromotive force is known,

$$C = .60\ \sqrt{\frac{S}{R}}.$$

Similarly for series wound magnets in which the current is known, the formula will give the greatest resistance which may be given to the coils in order not to heat too much; thus,

$$R = \frac{T\ S}{223\ C^2},$$

and if the limit is a rise of 80° F., the greatest allowable resistance will be

$$R = .36 \frac{S}{C^2}.$$

As these formulæ give the resistance at the higher temperature, allowance should be made for this increase in determining the resistance cold. Every degree Fahrenheit increases the resistance about two tenths of one per cent., (.2 per cent.) therefore at 80° above the normal temperature it would be $1 + (.002 \times 80) = 1.16$ times as great, and should therefore be divided by this number.

The same formula may be used equally well to find what the surface of a coil should be. Thus,

$$S = \frac{223\ w}{T}$$

which for a rise of 80° F. is

$$S = 2.8\ w.$$

As the number of watts to be allotted to the magnets is generally known approximately at the outset, this formula enables one to determine about what the least surface of the coils should be, and as the cross-section of the core is known, and by assuming a depth of winding of about $\frac{1}{8}$ the diameter, the least length of the core can readily be determined. This should, however, be used only as a guide, as the dimensions may have to be larger on account of the limited resistance of the coils.

In general, when the coils are short and have a great depth of winding, or when a relatively large percentage of the total energy of a machine is consumed in comparatively small coils (which is frequently the case in small, cheap, or poorly proportioned machines), the heating limit will determine the size of the coils, as the size calculated from the allowable resistance would give smaller values, which would cause too much heating. On the other

hand, when the coils are long and have only a few layers, or when the percentage of energy in the magnets is comparatively small (which is frequently the case with large well proportioned machines), the sizes will depend chiefly on the allowable resistance, as the heating limit will generally give smaller values. But these are only general rules; they may vary greatly in special cases.

Recurring to the formula for calculating the smallest allowable diameter of the wire directly from the required number of ampere-turns, namely:

$$d = \sqrt{\frac{.875\ (a\,W)\ l_m}{v}}$$

it is evident that its application is not limited to the particular case before stated, but that in general, it may be used in any case if only the ampere-turns, mean length of one winding, and the potential at the ends of the coils, are known; as the formula does not contain the current as one of its factors, it is not necessary to know this current to calculate the diameter of the wire. For instance, if only the potential of the exciter, and not its current, is fixed, or if a number of machines are to be excited in common by one exciter, the fields being all in multiple arc with one another, the diameter of the wire can be calculated without first knowing the current. After determining the diameter of the wire any suitable current may then be chosen, and when divided into the number of ampere-turns required, will give the number of windings of this wire. But this current is not only limited by other considerations to a certain range of values, which range may sometimes be quite great, but in most cases there will be one particular current which will, considering everything, be the most desirable in each particular case.

The principal considerations which limit the choice of this current, are the following. Suppose a very great current is used, and, therefore, a correspondingly small num-

ber of windings, then, as the potential remains the same, the energy in the coils will increase with the current and may exceed the heating limit, as the radiating surface is fixed by the known dimensions of the coil. The greatest allowable current should, therefore, be based on the heating limit and may be calculated from the surface of the coil and the potential, by one of the heating formulæ before given. But besides this heating limit, it may be restricted to a still smaller value by the desired efficiency of the machine, for it is evident that if the energy lost in the magnet coils be relatively great the efficiency of the machine will be poor. To calculate the current from this limitation, determine how much energy in watts may be allotted to the coils and divide this by the known potential, thus giving the current. The amount of energy to be used in the coils will vary greatly with different machines; in large well built machines it may be made as low as 1.5 to 2% of the whole output, while in small, cheap machines it often is as high as 10 to 20%. In large well proportioned machines this is the most important limitation for the current, provided, of course, that it does not exceed the heating limit as before described. As an increase of the current is accompanied by a nearly proportionate decrease in the quantity of wire, and therefore, also in its cost, it is evident that when cheapness of construction is of more importance than efficiency, the current should be taken as great as the heating limit will allow in order to economize wire, while if efficiency is the chief consideration the current should be as small as practicable. The smallest value which the current may have depends on the greatest amount of space which the coil may occupy and on the cost of the wire. If the current be taken too small the number of turns required to give the necessary ampere-turns, may be so great as to occupy more space than is allowed for the coil; furthermore, the depth of winding may then be so great that the mean length of one winding will become much greater than

what was assumed, and consequently the resistance of the coil will be too great to take its required current at the given potential. This minimum value of the current can readily be ascertained by calculating how may turns of the wire determined from the formula may be wound in the space allotted for the coil, and dividing this number of turns into the required ampere-turns, thus giving the current. It may be preferable in some cases not to decrease the current to this smallest value on account of the expense of the wire. As the formula for calculating the diameter of the wire gives that value which the wire must have to enable at least the required number of ampere-turns to be generated, it follows that this is the smallest diameter which the wire may have ; any larger size than this may be used without fear of increasing the resistance by the increased mean length of one winding due to the greater depth of winding.

From these considerations it will be seen that there is no fixed rule for determining the winding of the coils, but that there are certain limiting conditions differing in their relative importance in different machines, which give the designer some latitude in selecting the winding. As all these limitations can be readily calculated as described, from the known data, the most direct method of determining the winding of the coils appears to be, to calculate the limiting values for the current, the number of windings and the diameter of the wire, and then to choose such values within these limitations as will best meet the desired requirements of cheapness in first cost on the one hand, and good efficiency on the other. For instance, from the formula determine the smallest diameter which the wire can have ; from the heating limit, the surface of the coil and the potential, determine the greatest current ; from the desired efficiency determine again the greatest current ; from the coil space and least diameter of wire determine the greatest number of windings permissible ; from these, the best proportions will, in most cases, be-

come self evident. Should some of the limiting values be found to overlap, as for instance, if the smallest allowable current should be found to be greater than the maximum, it shows that the conditions cannot all be met by those proportions of the machine.

To illustrate this by an actual case, let it be required to determine the winding for a certain machine which generates 50 amperes and 100 volts. The exciter also has 100 volts, which is equivalent to assuming the first to be a self-exciting shunt machine. The frame is of the type shown in figure 26 with four coils. The cores are oval, the cross-section being 9x3 inches, having a periphery of 20 inches ; length of cores 10 inches. From the test with temporary coils it was found that 15,000 ampere-turns were required to excite the magnets while the machine was generating the required potential and current. To calculate the smallest diameter which the wire may have it is necessary to find the mean length of one turn. Assuming a depth of winding of about one-third of $3 = 1$ inch, the méan length l_m will be, from the formula

$$l_m = l + \frac{2\,c\,l}{a+b} = 23.3 \text{ inches.}$$

The diameter of the wire will therefore be, assuming a factor of safety of 20% by making $v = 80$ instead of 100,

$$d = \sqrt{\frac{.875\,(a\,W)\,l_m}{v}} = 61.8 \text{ mils.}$$

The nearest gauge number corresponding to this is No. 14 B. & S. which has a diameter of 64 mils. This is therefore the smallest wire which can be used, and is entirely independent of the current which may be chosen.

To determine next the greatest current from the heating limit, it is necessary to know the surface of the coils. The lengths of the outside and inside windings will be in the proportion

$$\frac{a+b+4c}{a+b} = \frac{9+3+4}{9+3} = \frac{16}{12} = \frac{4}{3}$$

in which a, and b, are the length and breadth of the oval, and c, the assumed depth of winding, which in this case is one inch. The inside length being from measurement 20 inches, the outside will be $\frac{4}{3} \times 20 = 26.7$ inches; and as the coils are 10 inches long, all four will have a total surface of $26.7 \times 10 \times 4 = 1068$ square inches. From the heating formula the greatest permissible current, allowing a rise of 80° F., will be, E being 100 volts,

$$C = .36 \frac{S}{E} = \frac{.36 \times 1068}{100} = 3.84 \text{ amperes.}$$

This should not be exceeded.

To ascertain next the greatest current considering the efficiency, determine what percentage of energy may be allotted to the magnets; as the machine is not large, six to seven per cent. should not be exceeded; assuming the latter gives 3.5 amperes as the greatest allowable current for that efficiency.

Finally, determine the least current or greatest number of windings from the coil space. A No. 14 B. & S. wire has an outside diameter of about 88 mils. As the coils are 10 inches long, there will be $\frac{10 \times 1000}{88} = 114$ turns per layer, and if the greatest allowable depth of winding is about one inch there will be $\frac{1 \times 1000}{88} = 11.4$ or about 12 layers making $114 \times 12 \times 4 = 5472$ windings on all four magnets. This gives for the least current $\frac{15000}{5472} = 2.75$ amperes, as there must be 15,000 ampere-turns. This current is considerably smaller than that obtained from the heating limit.

Summarizing these results, if the coils are to be wound as cheaply as possible, without regarding the efficiency, 3.8 amperes is the greatest permissible current. This gives $\frac{15000}{3.8} = 3950$ windings of No. 14 wire. On the other hand if the best efficiency is desired, the least possible current is 2.75 amperes, and 5472 windings of the same wire. As the cost of the wire of the same size, is approximately proportional to the number of turns, it will in the second case be $\frac{5472}{3950} = 1.4$ times as great as in the first case, while on the other hand, the percentages of energy in the coils will be 7.6 in the first and 5.5 in the second case. It is obvious that there would be no advantage in using a larger wire than No. 14, as the only apparent gain would be to reduce the resistance, thereby increasing the current and therefore decreasing the required number of turns or the length of the wire; but this current would be greater than 3.8 and would therefore increase the rise of temperature to more than 80° F. which was assumed to be the safe limit. On the other hand if a smaller wire than the one given by the formula were used the resistance would be so high that it would not be possible, with the same factor of safety, to generate the required number of ampere-turns in the limited coil space and with the given potential.

If coil spaces of the same dimensions be wound full with wires differing in size in each case, the coils will have the following relative properties if the space occupied by the insulation is not considered. If d represents the diameter of the wire, the number of turns will be proportional to $\frac{1}{d^2}$, that is, for a wire having twice the diameter the number of turns will be one-quarter as great as before, or with half the diameter they will be four times as great; the re-

sistance of the coils will be proportional to $\frac{1}{d^4}$. If the same number of ampere-turns are to be generated in each of these coils, the current must be proportional to d^2, and the electromotive force required to generate this current will be proportional to $\frac{1}{d^2}$ or to the number of turns; the energy in watts will then be the same in all the coils, and as the surface is the same, the temperature to which they will be raised by this current will also be the same. If instead of having the same number of ampere-turns these coils be subjected to the same electromotive force, as would be the case, for instance, in different coils for the same shunt machine, the current which will flow through them will be proportional to d^4, and the ampere-turns will therefore be proportional to d^2; the energy in watts being approximately equal to the current multiplied by the electromotive force, will then be proportional to the current (the electromotive force being the same) and will therefore be proportional to d^4, or to the square of the number of ampere-turns; as the surface is the same, the temperature will also be proportional to d^4, or to the square of the number of ampere-turns; furthermore, the energy required per ampere-turn or per line of force will be proportional to d^2. From this it will be seen that when subjected to the same electromotive force, any number of ampere-turns can be generated in a limited coil space by merely making the diameter of the wire great enough, but the heating of the coil will thereby be increased very rapidly so that a practical limit is soon reached, which may be determined from the heating formulæ; furthermore, the cost of generating the same amount of magnetism will increase as the square of the diameter, thus reducing the efficiency. If instead of having the ampere-turns, or the electromotive force the same in such coils, they have the same current passed through them, as for instance in different coils for the same series

machine, they will have the following relative properties: the ampere-turns will be proportional to $\frac{1}{d^2}$ or to the number of turns; the electromotive force consumed by the current will be proportional to their resistance, and therefore to $\frac{1}{d^4}$; as the current is the same, the energy required and therefore also the temperature will be proportional to the electromotive force, or to the resistance, or to $\frac{1}{d^4}$; the energy required per ampere-turn or per line of force, thus representing the cost of generating the magnetism, will be proportional to $\frac{1}{d^2}$. What was said regarding an *increase* of diameter of wire for shunt machine, applies therefore equally well to a *decrease* of diameter for series machines.

From this it will be seen that it is desirable in many cases (for instance in shunt machines) to find the smallest diameter which the wire may have. The formula, mentioned above, for calculating the diameter gives this minimum value under the given conditions, namely, that its resistance shall be such as to enable the required number of ampere-turns to be generated with the limited potential, and with the given mean length of one turn. While a smaller diameter than this would make the resistance too high for the necessary current and therefore render the coil useless, a larger diameter could, of course, be used, provided it is not limited by other considerations.

It may sometimes require less calculation to determine the winding indirectly by trial calculations by assuming different sizes for the wire and calculating the resistance and number of windings for each case to find whether the required number of ampere-turns can be generated in them.

While such a method may or may not be shorter it does not give the limiting values between which the designer can choose the one best suited to the case, nor does it indicate whether the best proportions have been arrived at, or whether any changes in the machine are advisable, or whether it is at all possible to meet the requirements. The direct method will therefore in most cases be found to be the shorter.

It is assumed that the dimensions of the frame, including the length and cross-section of the cores, have been determined as correctly as possible from the amount of magnetism required, prior to the determination of the winding of the coils. The calculated values of the diameter of the wire and of the necessary depth of winding, can therefore not be used to construct the cores from; they will however be found to be a convenient and reliable means of ascertaining whether the proportions of the cores and windings are the best, and if not, in what way they might be improved.

From the practical limitation to some of the proportions of the coils and from the general nature and size of the machine, it will readily be seen whether the calculated diameter of the wire is relatively small or large. Providing that the heating limit is not exceeded, and that the cores are not over-saturated more than is intended, then a relatively small value for the diameter of the wire indicates that either the ampere-turns are relatively small or that the potential is relatively great for those coils; in such cases a larger wire may be used if desired, provided the coil space is not too small, external resistance being added in case of a shunt machine to reduce the current to its former value. If on the other hand, the calculated diameter is relatively large, it indicates that either the magnet cores or the ampere-turns are relatively large, or that the potential is relatively small for those coils.

Similar deductions can also be made from the actual depth of winding as determined from the diameter of the

wire, in distinction from the assumed depth. If, as before, the heating limit is not exceeded, and the cores are magnetized to the desired degree of saturation, then if the depth is found to be very small it indicates that the cores are too long, while if it is very great it indicates that they are overworked, being too short. It is understood, of course, that the depth of winding need not be limited in all cases to a certain proportion of the diameter of the core, the rule given above to this effect is, as described, to be used merely as a general guide in order to enable the mean length of one turn to be calculated approximately. In most cases it will no doubt be found to be a proper proportion, but there may be other considerations, such as the heating, the limited coil space or the length of core, which may necessitate a greater or less depth than that assumed; if such is the case it will be shown by the calculations.

Similarly if it is found that the energy required for exciting the magnets is relatively great, the magnets are poorly proportioned or overworked, while if the energy required is found to be relatively small it indicates that the magnets are not used to their full capacity, and might therefore be made smaller. Such general and obvious deductions from the proportions of the coils will often serve as a guide and will be particularly applicable for reconstructing and standardizing machines, and in designing from poorly proportioned machines as models.

In all these cases it has been assumed that the potential at the ends of the magnet coils was a fixed and limited amount, and that a choice of the current necessary to meet the requirements was left to the designer ; these are the conditions for shunt machines. If on the other hand the current is limited to a certain fixed value, as in series machines, while the potential consumed by the coils may be made anything that is required, the calculations of the coils from the ampere-turns is slightly different. The current and the ampere-turns being known at the outset the number of turns is their quotient. The diameter of the wire

is then determined from the following limiting conditions: the limited coil space, the heating limit, and the desired efficiency of the magnets. The first may be determined approximately by multiplying the length of one coil by the allowable depth of winding, both in inches, and dividing this by the number of windings in one coil, the square root of this quotient is the diameter in inches including insulation; this is the maximum limit. The heating limit may be determined by finding the greatest allowable potential from the surface of the coils and the current, in the formula already given, namely

$$E = .36 \frac{S}{C},$$

which is then compared with the potential obtained from the desired efficiency; this latter, as described before, should be a certain percentage of the total voltage of the machine. From these two values the proper potential can then be chosen which will best meet the desired conditions of greatest cheapness of construction on the one hand (limited by the heating), or of best economy of energy on the other hand (limited by the efficiency). The diameter is then determined from this potential by the formula already given. This will give the smallest limiting value of the diameter. Or the diameter may be calculated directly for each of these two potentials giving two minimum values from which together with the maximum limit above given, the proper diameter can readily be chosen.

It is assumed herein that a machine is to be constructed which will generate a certain desired electromotive force and current. If, as is no doubt sometimes the case, the machine is built by guessing at the proportions and then running it to "see what it will give" such calculations as those described will not be necessary. But even in such cases the proper calculations made from the results of a test, may show whether the machine is running at its best or whether and how it could be improved in any of its parts.

Besides the formulæ already given, the following may sometimes be of use, especially as a check to determine the correctness of other calculations. Using the same letters and units as before, the resistance of the coils will be

$$R = .875 \frac{W l_m}{d^2} = \frac{3.5 \, W l_m}{4 \, d^2}$$

at about 70° F.; every degree Fahrenheit increases the resistance about two-tenths of one per cent. (.2 per cent.). If the calculated resistance is found to be too great, owing to slight inaccuracies in the diameter or assumed conductivity of the copper, or other unavoidable causes, the diameter can, if the coil space permits, be made slightly larger without fear that the consequent increased length will again increase the resistance, as the latter will increase only slightly with a greater mean length of one turn, while it will be diminished greatly by a slightly larger diameter. The potential lost in the coils is equal to

$$v = R a = .875 \frac{a \, W l_m}{d^2} = \frac{3.5 \, a \, W l_m}{4 \, d^2}.$$

The total length of wire, in feet, for all the coils may be calculated from the formulæ

$$L = \frac{W l_m}{12} = .0833 \; W l_m.$$

If e is the length, in inches, of one coil, d_1, the outside diameter of the wire in mils including insulation, and n, the number of coils, the number of turns per layer in one coil will be

$$\frac{1000 \, e}{d_1};$$

the number of turns per coil being $\frac{W}{n}$ and the depth of the winding being represented by c in inches, the number of layers will be

$$\frac{W d_1}{1000 \, e \, n} \text{ or } \frac{1000 \, c}{d_1},$$

or the thickness c, of the coil in inches will be approximately

$$c = \frac{W d_1^2}{1,000,000\, e\, n}.$$

The figures occurring in the formulæ for the heating of coils are based on the constants given by Prof. George Forbes in the paper before referred to. But as these constants may, and undoubtedly do, vary somewhat for different machines owing to their different general outlines, the ventilation, air blast from armature, exposed surfaces, etc., it is best whenever practicable to determine these constants for the particular style of machine, or for one similar in its cooling properties. This may readily be done by measuring the outside surface S, of the coils, finding their temperature T, in degrees Fahrenheit, after a long steady run with full load, and measuring the watts of energy w, which are consumed in the coils. Then $\frac{w}{T\,S}$ will be the constant to take the place of $\frac{1}{333}$ in the formula

$$w = \frac{1}{333}\, T\, S.$$

From this all the other heating formulæ can readily be deduced by substituting for w, its equivalents in terms of current, electromotive force or resistance. All heating formulæ are obviously only approximately correct owing to the greatly varying conditions, but if the limiting temperature is not taken too high, a moderate difference between the actual and the calculated heating will not be of any great importance.

The following formula by Brough, may sometimes be of use in calculating coils having a limited resistance. It is for determining the diameter d of the bare wire which, when insulated and wound to fill a limited coil space, will have the required resistance R. It is for circular coils only.

$$d = -i + \sqrt{i^2 + \sqrt{\frac{K\,e\,(A^2 - a^2)}{R}}}$$

in which i is the radial thickness of the insulation or *half* the increase in diameter due to insulation, e is the length of the coil space, A, the outer diameter of the circular coil, a the inner diameter, R the resistance of one coil, and K, the resistance of a piece of wire $\frac{\pi}{4}$ units long and one unit in diameter. All dimensions must be in the same units, either mils or inches. If they are all in inches, then K is about .000000687. For oval coils, which are by far the more common in dynamos, the writer has deduced the following similar formula in which, however, the quantities are given in the usual units, namely, d and i in mils, and the coil dimensions (c, depth, e, length and l_m mean length of one turn) in inches. It can be used for both circular or oval coils.

$$d = -i + \sqrt{i^2 + \sqrt{\frac{875000\,c\,e\,l_m}{R}}}.$$

In winding the coils it is very important to insulate the wire carefully from the core and at the ends of the coil. One or two layers of strong, tough and flexible cardboard about .015 to .020 inch thick placed around the core, and the same or even more at the ends, prior to winding the wire, will, in most cases, be sufficient. It is well to soak the cardboard in paraffine or thin shellac to keep it from absorbing moisture. When there are many layers, and particularly when very fine wire is used, it is well to place thin sheets of cardboard between every three or four layers, particularly under the outside layer, in order to keep them smooth and regular. For the sake of appearance, the last layer should always be wound full, which can readily be done when there are a large number of turns, by simply omitting or adding the odd number of turns,

but when the whole number of windings in the coil is comparatively small the odd number of turns should be wound in the next to the last layer, and the remaining space filled with cardboard, the last layer being then wound over all.

When the coils are oval it is well to wind them so that at the ends of the oval the wires lie in the position shown in figure 12, chapter v, instead of as shown in figure 13, as they may otherwise slip into the former position and thereby become loose, which should be carefully guarded against, as loose wires, by the vibrations of the machine, are apt to abrade their insulation.

The method of winding shown and described in chapter v, figure 14, bringing both beginning and end of the wire into the last or outer layer, may be used also in magnet coils, but as these are generally wound in lathes it would be attended with such difficulties that it will, in most cases, be impracticable.

In the ordinary method of winding, the inner end of the wire which has to pass out at the end of the coil, should be very well insulated with two or three extra insulations where it passes the other wires. A strong, hard cord wound closely around this part of the wire and afterwards shellaced and taped, forms a very good insulation. This end should be secured firmly where it leaves the coil to prevent vibrations of the wire. It is well to take one turn with this wire in the outer layer in order that if it should break off short at the coil at any time a splice can readily be made.

When the wire is thick and has been bent by having been wound once before, it may readily be straightened by drawing it, while it is being wound, through a series of grooved rollers as shown in figure 31. The tension necessary in winding may also be adjusted by these rollers. The practice of hammering the wire straight after it is wound is very objectionable, and should be resorted to only when absolutely necessary, and then only with great care.

An iron hammer should never be used for this except in connection with a piece of soft wood grooved at its end to fit the wire.

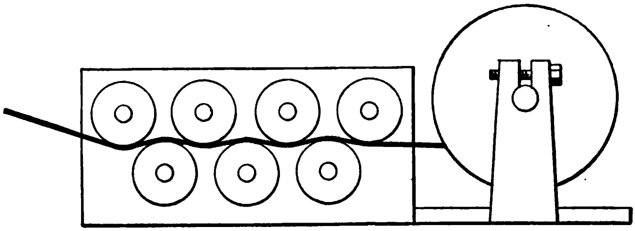


Fig.31

If it is desired to measure the length of the wire as it is being wound, it may be passed between two rollers of known circumference with a thin layer of leather or rubber on the surface, and an ordinary speed counter attached to the shaft of one of them, the length being calculated from the circumference and number of turns of this roller. If the apparatus in figure 31 is used, the speed counter may be attached directly to one of these rollers.

Magnet coils should not be connected in multiple arc unless there is no alternative, as there may be an unequal distribution of the magnetism, unless both the resistance and the number of turns is the same.

It is evidently unnecessary, so far as polarity is concerned, to wind the coils in any particular direction, and they may, therefore, always be wound in the direction which is most convenient, as they may always be so connected with one another and with the binding posts of the machine that the magnets shall have the proper polarity. The only object in winding the coils in particular directions is, that the connections between the coils and with the binding posts may be as convenient and as short as possible for the sake of appearance. In applying Ampere's laws to determine the direction which the current

must have in order to develop the required poles, it must be remembered to face the end of the coil. The current in the connecting wire between those ends of two coils which terminate in the same pole-piece, will describe the letter **U**, while that between those ends which terminate in the same yoke-piece, will describe the letter **S**.

In making the preliminary test to determine the required ampere-turns, it is well to examine the polarity of the pole-pieces with a compass needle (being careful that the polarity of the needle is not reversed in doing so), in order that the finished machine may be connected to have the same polarity. In self-exciting machines it is also well to note the direction of rotation and of the current of the armature, in order that all the connections in the finished machine may be made correctly at first, as much time may thereby be saved, particularly for more complicated connections, as in compound machines. In shunt or series machines, it is evident that with certain connections between the brushes and the magnet coils the machine will give absolutely no current.

As it is not always possible to carry out the specifications for a machine in all details, it is well to keep a complete record of all the parts and properties of each machine wherever they vary from the original determination or plans. Such records may often be of future use, especially for determining constants which may be of service in designing other machines, or in improving those already built.

SERIES MACHINES.

For the purpose of calculating the coils for the magnets, a series machine may be regarded as a separately excited machine whose exciter has a fixed, definite current and a potential which may be made as great as is required for the coils. Most of what was said above regarding separately excited machines in general, and this class in particular, applies, therefore, to series machines as well.

In making the test with temporary coils for determining the required ampere-turns, the magnets should be excited until the armature generates, not only the current and potential required for the external circuit, but in addition that which will be required by the magnets of the finished machine. This additional energy can readily be determined prior to testing the machine, it being a certain definite proportion of the whole output, as described above, depending on the size and desired efficiency of the machine. In a series machine the main current passes through the magnet coils, and therefore a certain amount of potential will be absorbed in the coils; in making the preliminary test for determining the ampere-turns, the armature should therefore be made to generate this additional potential by increasing the excitation of the temporary coils. For instance, if the external circuit requires 1,000 volts. and 10 amperes, and if 5% of the energy be allowed for the magnets, the exciting with temporary magnets should be continued until the potential at the brushes is 1,000 + 5% = 1,050 volts, when the current is 10 amperes.

The number of turns, being the quotient of the ampere-turns and the current, is readily determined. The diameter of the wire is then calculated, as described from the limiting conditions, namely, the limited coil space, the heating, the desired efficiency and the cost of the wire. In shunt magnets certain values of the diameter of the wire would make it impossible to generate the required ampere-turns, and it is therefore necessary to guard against this in such cases by careful calculations and by assuming a comparatively large factor of safety in the allowable resistance or potential; but in series machines the whole current must pass through the magnets, no matter what the size of wire; therefore such impossible cases do not occur, and these precautions are therefore not as necessary, while the factor of safety may either be omitted altogether or taken much smaller than in shunt machines, the latter being preferable as it is always more satisfactory to the constructor

to find the final results to be inside of the limit placed than beyond it. If for any reason the diameter of the wire has been taken smaller than it should be it will merely decrease the efficiency of the machine and increase the heating, but it will not prevent the machine from being used for generating the required output as would be the case in shunt machines.

The most important quantity to allow for in the factor of safety is probably the self-induction in the magnet coils, which acts to increase their apparent resistance. It is a question, however, whether this absorbs energy as a dead resistance would, or whether it acts more like a spring or a cushion, in which case no allowance in the factor of safety is necessary. With the usual solid iron cores it is probable that it acts like both. Its value depends on a number of quantities, such as the number of windings, the current, the number of armature coils, the speed of rotation of the armature and the nature of the iron cores; for ordinary machines 5 to 10% of the potential lost in the magnet coils will probably be a sufficient factor of safety to cover all contingencies in series machines.

As it is impossible to calculate such a complex machine as a dynamo with the same accuracy as is attainable in simpler apparatus, it may be found upon testing the finished machine that its output differs slightly from what was required. If the test described above for the empirical determination of the required ampere-turns has been made, almost all the errors and indefinite or indeterminate factors which enter into the calculation of a dynamo, have thereby been eliminated, as the chief elements of error occur in the calculation of the magnetism (which depends, among other things, on the quality of the iron, on the relation of the ampere-turns to the magnetism induced, and on the magnetic leakage), also in the calculation of the induction in the armature, in the self-induction, and in the adjustment of the brushes to the position of least sparking. These chief causes of inaccuracy having been

eliminated by the test for the ampere-turns, any differences which may be found to exist after the machine is completed, should be inappreciable or at least very small.

If it is desired to correct such differences, and if there is no regulator attached to the machine by which this can be done, the speed may be altered accordingly. To determine this correction for series machines, run the finished dynamo and adjust the resistance in the external circuit until the current is the required strength after the machine has been running with full load for a number of hours and has attained its highest temperature. Measure its speed, s, and the potential V, at the binding posts when thus running, then if the required potential is V^1, the speed at which it should be run, to correct for this potential, is

$$\frac{s\ V^1}{V}.$$

SHUNT MACHINES.

A shunt machine may, as far as the calculation of the winding of the coils is concerned, be considered as a separately excited machine whose exciter has a fixed potential, and the current from which may be made as great as is required for the coils. Most of what was said above, regarding separately excited machines in general, and this class in particular, applies, therefore, also to shunt machines.

In making the test for ampere-turns, with temporary coils, the magnets should be excited until the armature generates the required potential when the current is equal to that which is required in the external circuit and, in addition, that which is to be used in the coils. What was said regarding the potential absorbed in the coils of a series machine applies, therefore, equally well to the current required in the coils of a shunt machine.

The number of turns on the magnets is not always definite as in a series machine, but like the diameter of

the wire, is generally limited to a certain range of values, from which that which best meets the conditions for cheapness or for efficiency, may be chosen, as described before. There is a definite limit to decreasing the size of the wire and therefore to increasing the number of turns, for it is evident that when the wire is smaller than a certain fixed size, which can readily be determined for each case, the total resistance will be so high that the coils will not take the current required to generate the necessary ampere-turns. It is necessary, therefore, in shunt machines, to use a comparatively large factor of safety in order to guard carefully against passing this minimum value for the diameter or maximum value for the number of turns. The only way to correct such an error in the finished machine is to increase the speed. The maximum limit to the diameter of the wire is not so sharply defined, being dependent on the heating of the coils. Should the coils be required to generate a comparatively large number of ampere-turns in a small coil space, it may always be accomplished at the expense of the efficiency, by increasing the diameter of the wire, thereby increasing the current and diminishing the number of turns, provided only that the heating limit is not exceeded.

The factor of safety used in calculating the diameter from the formula is, as in series machines, dependent on a number of factors. In ordinary cases 20 to 25% will probably be sufficient, depending on the number of errors which must be allowed for.

Should any slight differences be found to exist between the actual and the desired output of the finished machine, they may be corrected by a slight alteration in the speed. An increase of the speed will evidently increase the induction in the armature, that is, the potential at the brushes and at the magnet coils; this will increase the current in these coils, and, therefore, the magnetism, which will again increase the potential. A slight increase in speed will therefore increase the potential in a much greater propor-

tion. For small differences it may be assumed to vary approximately as the square of the speed. To make this correction, run the finished machine until it has attained its highest temperature, and adjust the external resistance until the current has the proper strength, independently of the potential. Measure its speed, s, and the potential V at the binding posts when thus running, then if the required potential is V^1 the speed at which it should be run to correct for this potential is

$$s \sqrt{\frac{V^1}{V}}.$$

COMPOUND MACHINES.

As the magnets for compound machines generally consist of both shunt and series coils, their winding is governed by the same general principles as those given above. There remains only to determine how much of the required magnetism is to be generated by shunt coils and how much by series coils, which can readily be determined from the functions of these coils. For instance, in a simple shunt machine the difference of potential at the terminals will fall with an increase of the current, because there will be more of the potential absorbed in the machine itself in sending the increased current through the armature, thus making the useful or available difference of potential so much less. This will in turn diminish the current in the shunt coils, which will, by decreasing the magnetism, diminish the potential still more. If, therefore, constant potential is desired in a simple shunt machine, it will be necessary to make the armature resistance exceedingly small in order that the potential which is absorbed in it will be inappreciably small as compared with the total electromotive force of the machine. Although this can be done it is probable that the shunt machine will thereby become very large and heavy as

compared to the output. If, however, series coils of a certain number of turns be added to the shunt coils, an increased current in the armature by passing through these series coils will increase the magnetism just enough to regenerate the increased potential absorbed in the armature by the greater current, and therefore the available or useful potential will be kept constant. The function of the shunt coils in a compound machine is, therefore, to generate the required potential for a small current, while that of the series coils is to generate the potential absorbed in the machine itself. For an armature with a relatively small resistance there will be required only a few turns in the series coils, while if its resistance is relatively great the number of series turns will have to be proportionally greater.

If the series coils have a relatively high resistance, due either to a comparatively large number of turns or to a limited coil space, the potential absorbed by them will become appreciable and will again cause the potential of the machine to fall with an increase of current. This can readily be corrected by adding a few more turns of the series coils to regenerate this lost potential. When constant potential machines are used for incandescent lights there is a certain amount of potential lost in the leads which increases with the current; the lamps will consequently grow less bright as more of them are turned on. In order to correct this, the writer suggested some years ago, to wind such compound machines, not for a constant potential as was usual, but for a potential which increases with the current, in order that the available potential at the lamps and not at the machine remains constant for all currents. This is done by simply increasing the series windings still more, in order to correct for the loss of potential in the leads in addition to that lost in the series coils and in the armature. Such machines are now largely used in place of the older constant potential machines. The chief advantage obtained, apart from the constant

brightness of the lamps, is that the loss in the leads may then be made comparatively great, 15 to 20%, or for great distances even 30%, by which a great saving of copper will be gained, the cost of the additional lost power in the leads being small as compared with the interest on the cost of the copper of the leads if this loss were made small.

There are two methods of making the connections of compound machines, shown diagrammatically in figures 32 and 33. In the first of these, known as the ordinary compound machine, the shunt coils marked *Sh* are connected to the brushes, while the whole external current flows through the series coils *Sr*, the binding post of the machine being + and — *P*. In the second method, figure 33, known as the "long shunt" compound machine, the shunt coils are connected to the poles of the machine instead of to the armature brushes, and, therefore, the whole armature current passes through the series coils. The differences in the two methods will become more apparent when considering the calculations of the winding. In large, well proportioned machines with few series windings, the differences are very slight if at all appreciable.

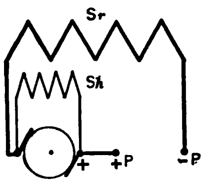


Fig. 32

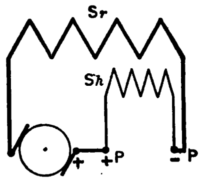


Fig. 33

The test with temporary coils for ascertaining the required ampere-turns should be made in the same way as before, but instead of testing the machine for full load only, the test should be continued for a large number of different loads, say 15 to 20, varying from full load down to open circuit, measuring in each case the ampere-turns

which are required to excite the machine to the desired potential at the armature. Before making this test the machine should be examined for magnetic saturation, as will be described in a subsequent chapter, in order to ascertain whether the iron of the frame is properly proportioned for compound machines and to find what the maximum limit to the ampere-turns is. It is very necessary in compound machines not to have them over-saturated and to have the useful magnetism increase as nearly proportional to the magnetizing current as possible, which is most nearly accomplished by having much iron of good quality, evenly distributed and not too near saturation, otherwise there will be only a rough approximation to self-regulation.

The proper position of the brushes should be ascertained and fixed once for all; it should not be required to be altered for different loads, for it is evident that the machine is not self-regulating if the brushes require to be

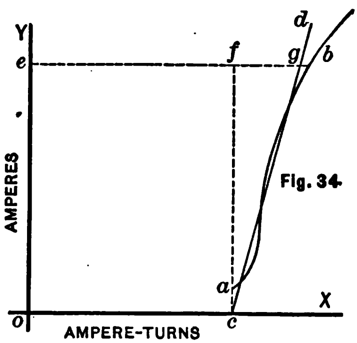


Fig. 34.

adjusted for different loads. A well proportioned compound machine should not spark perceptibly for the same position of the brushes, even when the full load is thrown off and on suddenly.

Having made all these tests and adjustments, the com-

pounding of the coils may be calculated according to the following method, which will be limited to machines compounded for constant potential at the machine or at the lamps, as these are the only kinds that have been found practicable. On a piece of cross sectional paper lay off along the vertical line, *O Y*, figure 34, on any convenient scale, the currents which the machine generated in the above described test, and along horizontal lines through these points lay off the ampere-turns required in each case to excite the machine for constant potential, and draw a line, *a b*, through the points thus located. This line will, even in the best machines, be somewhat curved, particularly at the ends. The magnetization of the machine should not be continued beyond the point marked *b*, where the line begins to have a decided curvature, as the compounding is possible only for the tolerably straight portion of the curve. Draw a straight line, *c d*, through the most important points of the line, *a b*, that is through such points at which the machine is to be used most frequently; this line will then represent the nearest approach to constant potential for that machine; the greater the variation of the straight from the curved line the greater will be the variation of the potential from a constant. The deviation from this straight line will therefore show at once whether the machine is suitably proportioned for being wound for constant potential.

This line *a b* represents a certain proportion of the series and shunt coils. The horizontal distances between it and the line *O Y* represent the ampere-turns required for the respective currents in the external circuit. These distances are made up of a constant portion, *e f*, and a gradually increasing portion, *f g*, which is greater in proportion to the external current. As the shunt coils are to be connected to the poles of the machine or to the armature where the potential is to be constant, the current in them and, therefore, the number of ampere-turns is constant for all loads. The constant portion *e f* or *o c* of the whole number of

ampere-turns should therefore be allotted to the shunt coils, and as the ampere-turns of the series coils increases in proportion to the current in the external circuit, that portion of the whole number of ampere-turns which lies between $f\ c$ and $d\ c$ should be generated by the series coils. The shunt coils are therefore calculated as for an ordinary shunt machine requiring the ampere-turns represented by the distance $e\,f$ or $o\ c$, while the series coils are calculated as for an ordinary series machine requiring the ampere-turns represented by $f\ g$ when the current is that represented by $o\ e$.

The total energy allotted to the magnets, should be divided between the series and the shunt coils in proportion to the ampere-turns generated by them respectively, at full load, the series coils absorbing potential, and the shunt coils current. In determining the coil space for the shunt coils, care should be taken to correct for that occupied by the series coils which are usually wound first, as the real resistance might otherwise be considerably higher than the calculated, owing to the increased length. In determining the heating limit to the diameter, the total maximum number of watts which may be dissipated in the coils may be calculated from one of the formulæ given above, the cooling surface being that of the outside coil only; this total may then be divided between the coils in proportion to their number of ampere-turns, or in any other proportion provided only that the sum of the watts lost in both does not exceed this total.

The general method just described, applies only to large, well proportioned machines, or to others when only a rough approximation is desired; for smaller machines, or when the machine is to correct for loss of potential in the leads for incandescent lamps, or in cases where accuracy is desired, certain corrections are required in the calculation of the compounding of the coils. These corrections will be different, according to which of the two connections shown in figures 32 and 33 are used; they may be briefly

described by the following diagrams, their importance in different cases being rendered apparent by their actual values. Referring first to figure 32, it is evident that if the shunt current is appreciably great, it should be subtracted from the armature current to give the real external and series winding current. In figure 35, therefore, in which *c d* represents the same as *c d* in figure 34, this shunt current should be laid off at *o h*; the external or series winding current should, therefore, be measured from *h*, instead of from *o*, and the shunt winding calculated for *h i* ampere-turns instead of *o c*. Furthermore, if the potential is constant at + and — *P*, figure 32, it will have to increase slightly at the terminals of the shunt coil for full load, owing to that consumed in the series coils, which will be appreciably great when the armature resistance is relatively great; the magnetization of the shunt coils will, therefore, increase slightly with an increased load, instead of being constant. This increased potential for the great-

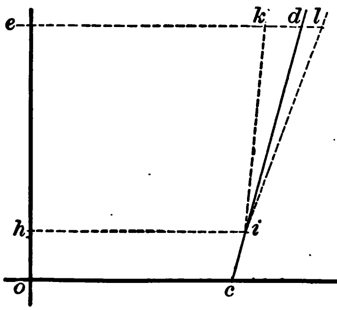


Fig. 35

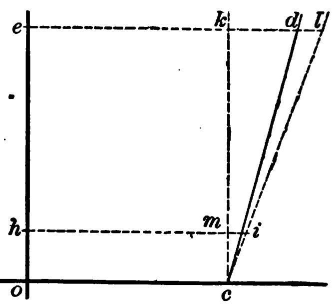


Fig. 36

est load can readily be calculated by Ohm's law from the resistance and current in the series coils; let this be v, and let V be the potential at the poles + and — *P*, then that at the shunt coils, for full load will be $V + v$; if *h e* is the maximum external current lay off *e k*, so that it bears the

same proportion to $h\ i$, as $V + v$ does to V; in other words, make $e\,k = \frac{V + v}{V}\ (h\ i)$, then $e\,k$ will represent the magnetism of the shunt coils at full load, and will be slightly greater than $e\,f$, figure 34. The potential v, lost in the series coils must be generated again by a few additional windings of the series coils ; if it takes $e\,d$ ampere-turns to generate V volts, it will require $e\,l$ ampere-turns to generate $V + v$ volts, in which by simple proportion, $e\,l = \frac{V + v}{V}\ (e\,d)$. The line $l\,i$, therefore, represents the correction of the line $d\,i$, and the series coils should be calculated from the ampere-turns represented by $k\,l$, and the external current, $h\,e$, instead of from $f\,g$ and $o\,e$, respectively, in figure 34.

If the connections are as in figure 33, these corrections will be slightly different. If the potential is constant at $+$ and $-$ P, the current and magnetization of the shunt coils is constant, and no correction is necessary for them. In figure 36, therefore, lay off as before, $o\ h$, equal to the shunt current, then $h\,m = o\,c$, will be the shunt ampere-turns. To correct the series coils for the potential lost in them, lay off $e\,l$, determined as in figure 35, then $l\,c$, will be the correction of the line $d\ c$, and the series coils should, as before, be calculated from the ampere-turns, $k\,l$, and the current $e\,h$. In both figures 35 and 36, these corrections are greatly exaggerated for the sake of clearness. As the shunt current in figure 33 must also pass through the series coils, they act to a certain extent as shunt coils also, though they should not be included in the calculation of the latter. In figure 36, $m\ i$ represents the ampere-turns which are generated in these series coils by the shunt coil current.

If the machine is furthermore to correct for the fall of potential in the leads, the simplest way to determine the

winding, is to make the test for ampere-turns by passing the main current through a resistance equal to that which the leads are to have, and thence through the lamps or other resistance, and to excite the machine so that the potential at the end of this lead resistance remains the same for different loads. The calculations are then made as before, except that the potential at the shunt coils is not that measured at the ends of these leads, but that at the machine, which is, of course, higher, and may be either measured during the test or calculated from the resistance of the leads and the current. If this test cannot conveniently be made with a resistance equal to that of the leads, the correction of the ampere-turns may be calculated in the same way as described above for correcting for the loss in the series coils, except that the shunt coils are not determined from the potential at the ends of these leads, but only from that at the machine.

The relative values of the two methods of connecting, shown in figures 32 and 33, may be seen by comparing figures 35 and 36. When the corrections, shown exaggerated here, are small, the two methods are practically the same, which will be the case for large, well proportioned machines. In small machines these corrections become more important, in which case there will probably be a slight advantage in favor of the second, as the shunt coils, which are the more expensive, are somewhat smaller, as seen from the distance *h m*, figure 36, compared to *h i*, figure 35, besides being subjected to a lower potential; the series coils are consequently somewhat larger, but the whole coils will be less bulky than in the first method.

Figure 34, as well as the corrections shown in 35 and 36, indicate what the most desirable general proportions are for compound machines. The curved line, *a b*, should be as straight as possible, which may be accomplished by using a good quality of soft iron in the field, by making the cross-section large enough to be well below the point of saturation, and by distributing it so that all parts are

magnetized to about the same degree, instead of having some parts over-saturated while others are far below saturation, as is often the case. Furthermore, the inclination of the line *c d*, to the vertical should be as small as possible, as the variations of the potential which the series coils have to correct will then be less. This is accomplished by making the armature resistance as small as practicable. To avoid shifting of the brushes, the number of armature windings, and particularly the number of windings per armature coil, should be as small as possible. In general, all that was said in previous chapters regarding the most desirable proportions of armature and field, applies particularly to compound machines, as it is of the greatest importance to have these well proportioned. The magnets should respond quickly and readily to changes of magnetization, in order that regulation may be easily effected by the ampere-turns, over-saturation or even too close approximation to saturation should, therefore, be carefully guarded against.

From the principles of constant potential compound machines, it is evident that they will be self-regulating only for variations in the current, but not for variations in the speed or in the resistance of the coils due to heating, neither of these can be compensated for by compound winding, and it is, therefore, necessary to maintain both the speed and the heating as nearly constant as possible. Furthermore, it is necessary to run the finished machine at the same speed as that in the test, as the proportions of the series and shunt coils will be quite different for different speeds. The calculations should be made as carefully as possible, as it is not possible to correct any mistake by changing the speed as in simple shunt or series machines. If, however, a final correction is found necessary, the speed may be increased and an adjustable resistance placed in series with the shunt coils, and one as shunt to the series coils ; these can be adjusted by trial to compensate for the error, and should then remain unaltered for varying loads;

from the functions of the shunt and the series coils, it can readily be seen which of these two should be adjusted.[1]

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1. For further information regarding the winding of field magnet coils, the reader is referred to the author's "Practical Directions for Winding Magnets for Dynamos."

CHAPTER IX.

Regulation of Machines.

THE simplest and often the most convenient way of regulating or adjusting the current or potential which is generated by a machine, is to move the brushes toward or from the neutral line. It has been shown in chapter iv that the halves of the continuous winding of an armature are connected in multiple arc with each other, and that the total electromotive force generated in each half is equal to the sum of the electromotive forces of the separate coils in that half; if, therefore, the brushes are moved away from the neutral line, say a distance equal to the width of one commutator bar, it is evident that one coil on each side of the armature will thereby have been switched from one side to the other of the line joining the brushes (see figures 6 or 8, chapters iv. and v). As the direction of the induced current will tend to remain the same in these two coils, it will evidently be opposed to the other coils as now connected, and will therefore diminish the available electromotive force at the two brushes. For instance, if there were 64 armature coils and if each coil generated three volts, there would be 32 coils in series in each half, giving $3\times32=96$ volts; if now the brush be moved the width of one commutator bar, there would be 31 coils left, generating 93 volts, but these would be opposed by the three volts of the coil which was added, thus leaving 90 volts. This will continue to decrease by continuing the displacement of the brushes until they have been moved through 90° when the coils will all oppose and neutralize each other. In actual practice the results would be modified somewhat, quantitatively, as the electromotive force

induced in the coils near the neutral line is generally less than in the others, thus making the regulation more gradual at first ; furthermore, the direction of magnetization of the armature by its own current, will, of course, follow the movement of the brushes, and therefore will tend to move the neutral line in the same direction; but in well built armatures with few windings, this effect will be small if at all appreciable, as the magnetization due to its own current will be small as compared to that due to the field.

This method of regulation is evidently equally well applicable for adjusting the current in the external circuit, as well as the electromotive force, for the former may always be regulated by proper adjustment of its electromotive force. It is furthermore evident that by thus diminishing the electromotive force or current, or both, a nearly proportionate amount of power will be saved, as the opposing electromotive force does not generate an opposing current, and therefore no energy is required by it. This can be shown by moving the brushes through about 90°, in which case no current will be generated and the dynamo will run light, that is, without consuming power.*

An objection to this form of regulation, and one which makes it prohibitive in most cases, is that it generally causes very bad sparking when the brushes are too far from the neutral line. It is well known to all who have adjusted the brushes of a dynamo, that there is one definite position, and generally only one, in which there is least sparking, and that the sparking is increased by altering this position. This is partially due to the fact that at least one coil is continually short circuited by each brush, and when the brushes are moved too far from the neutral line this coil, instead of being "dead," that is, without an induced electromotive force in it, is "alive," that is, has electromotive force induced in it, and therefore on being short circuited, it will have a more or less great local current circulating in it, which, even if the electromotive force is small, may be very great, as the resistance is small ; when

this current is broken at the end of the brush, it evidently will spark more or less badly.

This method of regulation, when not accompanied by any regulation of the field, is therefore not to be recommended, except for small machines in which the sparking is not objectionable, or for machines with many armature windings and weak field in which the neutral line will shift with the brush line, or in such inferior machines in which the sparking is very bad in all position of the brushes, or in such machines as the Thomson-Houston in which the evil effects of the sparking are avoided to a great extent by a blast of air between the commutator bars.

It may be remarked here that the position of the brushes which gives least sparking, is not always coincident with the position for greatest electromotive force. It is evident that they should always be adjusted to the former and not to the latter, which may always be accomplished by determining the winding of the magnets as described in the last chapter.

The second method of regulating the electromotive force, and therefore the current, is to vary the speed of the dynamo, but as this is in most cases impracticable, it need not be discussed here. What was said in previous chapters concerning the effect of the speed will enable one to determine the amount of the adjustment; for instance, the effect of a certain change of speed is much greater for a shunt than for a series machine, under certain conditions in the external circuit. A change of speed may in many cases be accompanied by a change of position of the line of least sparking, and should in those cases be accompanied by a change of position of the brushes.

A third method of regulation is to use a variable dead resistance in the external circuit, which will absorb a certain amount of energy, thus enabling the rest of the energy, that is the useful part, to be adjusted. As this method wastes energy, its general use is not to be recommended; but in certain special cases, belonging more particularly to

the subject of systems of distribution rather than dynamos, there are advantages gained by this method which cannot be attained as readily by other methods, or in other words, the advantages gained are commensurate with the cost of the wasted power. To calculate the most economical form of such resistances, proceed as follows: determine by calculation, or preferably by trial under actual working conditions, what the difference of potential, V, is, which must be absorbed by each of the successive adjustments of the resistance; also the current C, which flows through the resistance in each case; the quotients $\frac{V}{C}$ will be the resisances. If german-silver wire or flat bands are to be used, their cross-section is next determined from the heating limit. If convenient and reliable formulæ are at hand this may be calculated directly, the necessary length being then readily determined from this cross-section, the resistances $\frac{V}{C}$, and the specific resistance of german silver. But in the absence of such formulæ, or if the specific resistance of the german silver (which varies greatly) is not known, the following experimental determination will be found reliable and simple: Take as long a piece as convenient of the wire or the bands of which the resistances are to be made, measure its length, and mount it as an open spiral or otherwise, as it is to be mounted in the finished resistance. Pass a current through it from a dynamo or battery, and increase this current slowly until the wire has been raised to as high a temperature as is permissible, allowing sufficient time for the temperature to attain its greatest value; then measure the current c, passing through it, and the difference of potential v, at the terminals of the wire. The length of the wire (of the same cross-section) for the required resistance which is to absorb V volts, will then evidently be, V divided by v, and multiplied by the length of this trial piece; the number of such wires which must

be placed in multiple arc in the resistance for the current C, is evidently C divided by c.

By mounting this trial wire in different ways, and raising it in each case to the same temperature, the most economical method of mounting may readily be determined; the object is, of course, to present as much surface to the free access of air, as possible. Up to a certain limit, differing under different conditions, it will be found to be more economical to use a larger number of small wires in multiple arc, rather than a smaller number of larger wires.

This method of experimentally determining the resistance wires, applies only to those cases in which the wires are all of the same size as the test wire, their number in multiple arc being then made proportional to the current. If different sizes of wire or bands are to be used, they must be calculated by means of the well-known heating formulæ for wires. In many cases the following modification of the formula will be found convenient for round wires: Make the same test as before, with any convenient wire, measuring merely its diameter, say in mils, and the maximum current. Cube this diameter, and divide it by the square of the current; this will give a number or constant, which can be used to calculate the diameter of any other wire of the same material, but for a different current which will not heat it to a higher temperature than that of the test wire. For instance, if C, be any other current, square it and multiply it by this constant, the cube root of this will then be the diameter in mils, which the wire must have, in order to carry this current and not to heat any more than the test wire. The required length of the wire is then determined from this cross-section and the resistance which it must have.

If bands of different width, but of the same thickness are used in place of wires, the width should be proportional to the current. If they are of the same width but of different thicknesses, the thickness should be proportional to the square of the current. This shows that it is

much more economical to use bands as thin and as wide as possible.

The fourth and most common method of regulating the electromotive force or current of a dynamo, is to vary the strength of the magnetizing current or the ampere-turns of the field magnets. The method of effecting such adjustments of the magnetizing current will evidently be different according as the machine is shunt, series, or separately excited, and also whether the machine is to be regulated for constant potential or constant current. In all these cases, the electromotive force of the machine, but not necessarily its current, will be nearly proportional to the magnetizing current, provided the magnets are not oversaturated; in the latter case the strength of the magnetizing current must be varied through a greater range, to produce the same change in electromotive force. The current in the external circuit will, of course, depend on the resistance of the circuit, and on the electromotive force, and must therefore be adjusted for different resistances by varying the electromotive force.

Separately excited machines are regulated by adjusting the current strength of the exciter. This can be done by a variable resistance in this exciting circuit, or better, by regulating the field current of the exciter itself by any convenient method. The former does not waste much power as it consumes only a fraction of the energy for the field current, which latter is itself only a small fraction of the total power.

Shunt machines are regulated by an adjustable resistance in the magnet circuit. If the machine is to be regulated for constant potential, as when used for incandescent lamps in parallel, the amount of this regulation is dependent on the resistance of the armature, and will therefore be small for low resistance armatures. The amount of this resistance is most readily determined by an actual trial, that is, by running the machine first with full load and then with no load, and adjusting in each case any convenient resistance

in the magnet circuit until the difference of potential at the poles of the machine is normal. Measure these two resistances, as well as the current which flows through them. The smallest allowable cross-section for the resistance wire is then determined from this current, as described above, and its total length is then calculated from this cross-section and the total resistance. The wire is then mounted so that successive parts of it may be switched into the magnet circuit, the number of such parts (usually from 10 to 20) depending on the desired nicety of the regulation. As the variation in the current through this resistance is comparatively small, one size of wire will usually suffice for the whole resistance; if, however, the current varies considerably, it will be more economical to use different sizes of wire for different parts; they may be calculated from the heating formula given above. Such machines are usually wound as described in the last chapter, so as to enable some resistance to be placed in the magnet circuit even at full load, for the purpose of adjusting for slight irregularities, such as the heating of the magnet coils, lowering of the speed of the engine, etc. The variation required between full and no load is of course due to the difference between the electromotive force and the difference of potential, as described before, and therefore depends on the armature resistance. The energy wasted in the resistance is insignificantly small.

If the shunt machine is to be regulated for constant current with consequent great variations in electromotive force, as for instance in an arc light machine for a varying number of lamps, the determination of the required resistance is best done experimentally as described above, only that it must be determined for a large range of values, and not merely for the two extremes. The reason for this, is that this resistance does not vary in proportion to the electromotive force, as the latter will itself vary the current in the shunt magnet circuit. It may even be found that the resistance must be varied first in one direction and then in

the other, for regular diminutions of the electromotive force. The current in the magnet circuit should also be measured, and if it varies considerably, the resistance wires may be made of different sizes for the sake of economy. The successive steps of the adjustable resistance may have relatively different values to effect a regular increase of electromotive force. As shunt machines for such high potential as would be required for many arc lights in series would necessitate the use of a very large amount of quite fine wire for their magnet coils, they become very expensive and are therefore not used very much. They possess no particular advantages over the ordinary series machines if the latter are, as is usually the case, automatically regulated, and therefore not subject to the destructive effects of the unavoidable short circuits in the external circuit.

Shunt machines may also be regulated by winding the magnet coils in independent sections; by means of a switchboard to which the terminals are attached, these sections may be successively cut out or switched into the circuit, thus varying the ampere-turns of the magnets. But as this complicates the construction greatly and has no particular advantage over the other method, it is not practiced to any great extent.

Series machines for constant current may be regulated by winding the magnet coils in sections as just described, but the same objections apply here as well. A modification of this, is to solder smaller branch wires to different parts of the coils and by means of a suitable switch-board, to which these wires are led, short circuit the successive sections. But though this is an improvement of the method, it possesses in general no particular advantages over the next method to be described. In some particular cases the advantages may be sufficiently important to justify its preference over other methods. In such cases, care should be taken to cut out the successive sections so as not to unbalance the field.

The simplest and most usual method of regulating series machines is to use an adjustable resistance as a shunt to the magnet circuit, that is, to connect an adjustable resistance between where the main circuit enters and where it leaves the magnets. The successive steps of such a resistance may be best determined by an actual trial with any convenient resistances, which are afterwards measured and serve to calculate the length of the resistance wire. If the magnets are not over-saturated the resistances may be calculated (knowing the resistance of the magnet coils), so as to shunt off such portions of the main current as will leave the magnet current proportional to the electromotive forces to be generated. But owing to the fact that the unknown self-induction of the magnet coils acts to increase their resistance, and also to the fact that the brushes will in many cases be required to be adjusted together with the field, owing to the shifting of the neutral line, such calculations will not be very reliable, and it is therefore best to eliminate all such inaccuracies by an experimental determination. In this test the current which is shunted around the magnets and through the resistance, should be measured for each successive step, and from this the cross-section of the resistance wire is determined by the heating limit, as described above. This current will vary from almost nothing for the maximum resistance, to almost the whole main current for the smallest resistance, thus requiring quite different sizes of resistance wires for different steps of the regulation. Machines regulated in this way may readily be adjusted to maintain a constant current even for a short circuit. The energy wasted in this resistance being a fraction of that used for the magnets is not significant.

Series machines might also be regulated in this way to maintain a constant potential for variable currents in the external circuit; but a simple calculation for an actual case will show that in order to maintain the constant potential for a small current in the external circuit, the field magnet coils would have to be wound with comparative

small wire, and that, therefore, very much current would have to be shunted through the adjustable resistance when the current in the external circuit is a maximum. This would necessitate resistances of large size, and would waste considerable energy when the machine is doing its greatest work. Such a system should, therefore, if used at all, be limited to cases in which the range of adjustment is quite small, as for instance to machines which are used with a nearly constant load of lamps. The advantage of such machines over a shunt machine is evidently the saving in the cost of the wire and winding of the magnet coils. For a comparatively high resistance armature there will be less regulation required for constant potential; this method is, therefore, applicable best for small, cheap machines for nearly constant loads.

All the methods of regulation described may be made automatic by the addition of a proper mechanism which automatically alters the resistances, position of brushes, etc. Such regulators consist essentially of two parts, first, the detector, the object of which is to detect changes in the potential or current which is to be maintained constant, and second, the mechanism which is actuated by this detector and which effects the necessary changes in the resistances, sections of coils, brushes, or speed. Numerous more or less effective automatic regulators of this kind have been devised, some of which have proved to be very satisfactory. As they have been described in detail in text books and periodicals, it is not necessary to repeat the description here.

CHAPTER X.

Examining Machines.

AFTER a dynamo is completely finished it is well to subject it to a thorough examination, not only for the purpose of being assured that it will run properly, but also to find out whether it is properly proportioned in all its parts, or whether it could have been improved in some of its proportions, and if so, what proportions are faulty, and to what extent they could have been improved. It will likewise show whether the machine is run under the most advantageous conditions, and if not, what changes would enable it to be run so. The data which may be obtained from such examinations when properly made, will often be found to be of great assistance in designing other machines of different sizes, proportions and styles.

As these tests may sometimes show faulty construction or proportioning, it is well to make some of them while the machine is wound with temporary field magnet coils, that is, before it is finally wound with its proper coils. This applies more particularly to the saturation and the heating tests, as also to the test for the effect of the counter magnetization of the armature. Some of these tests will, of course, be different according as the machine is separately excited with temporary coils and an exciter, or whether it is self-exciting, as a shunt, series or compound machine.

Among the most important of these tests is the determination of what are called the "characteristics" of the machine. These are the results of a succession of tests plotted in the form of a curve, which then shows graphically some of the more important features of the machine. Such curves will show at a glance how one quantity, say

the electromotive force or current, will change, when changes are made in another quantity, say the external resistance, speed, or magnetization. For instance, let a series wound machine be run at a constant speed, and let it discharge through a succession of different resistances (which need not be measured) varying from a very large one to as small a one as the machine will stand without injury. Measure both the difference of potential at the terminals, and the current, for each resistance. On a piece of cross-section paper lay off these different currents to any convenient scale, along the horizontal line O X, figure 37, from O to the right; similarly lay off the differences

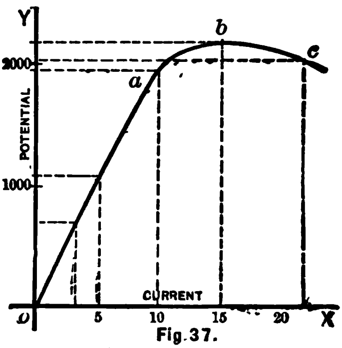


Fig. 37.
SERIES MACHINE.

of potential from O to Y on the same or on any other convenient scale. The intersections of the vertical and horizontal lines drawn through each two corresponding values of the current and difference of potential respectively, will give a series of points, the curved line *o a b c* through which will be the characteristic for the current and potential of that machine. This curve shows at a glance that when the currents are small the potential increases rapidly with an increase of current; and as the first part of the curve is a straight line it shows that the potential increases in

the same proportion as the current. When the current has been increased to a certain value, in this case ten amperes, the potential no longer increases so rapidly, and at fifteen amperes it has reached a maximum limit; for still greater currents the potential falls again. From this characteristic the following deductions can be made. Barring other considerations, this machine should not be run normally for currents or potential less than those of the point *a*, for if it is, the curve shows that it is not running to the best advantage, or in other words, the machine is larger than it need be. It should not be run much beyond the point *b*, as that is the maximum point for the potential, and it is probable that the machine heats greatly beyond this point, and therefore runs at a disadvantage and with poor efficiency. Furthermore, for values of the currents between *a* and *c* the machine will give a nearly constant potential for different loads, the variations in the potential being less the nearer this part *a c* of the curve approaches a horizontal, straight line. The curvature at *a* is due to the iron having become saturated, and shows that a greater current in the series coils than that for *a* has little effect in increasing the magnetism, and therefore, the potential; series wound machines for arc lights in series may therefore be run above the point *a*, because changes in the current due to poor regulation of the lamps, will then have less effect in causing the potential to change, in other words, the magnets are less sensitive to changes of current beyond the point *a*, and, therefore, the current will be more nearly constant.

In the same way the characteristic may be drawn between the known external resistance and the potential, showing how the latter will vary for different external resistances. Similarly, that for the resistance and current will show how the latter will vary with changes in the former, and between what values of the resistance the current will be nearly constant. By running the machine at different speeds and discharging through the same fixed

resistance, the characteristic for the speed and current, or speed and potential may be obtained. Or if the resistance is also varied for each speed a succession of curves, like that in figure 37 will be obtained, showing the effect of changes of speed. But in general, characteristics involving changes of the speed, though interesting and instructive, are of less practical value, as it is assumed at the outset that the speed is as great as mechanical considerations will permit, as pointed out in another chapter. The speed characteristics become important when it is desired to shift

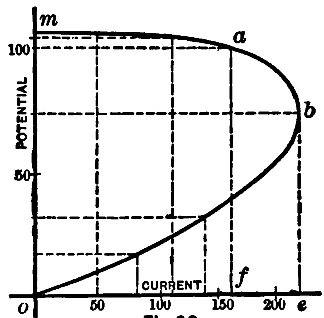


Fig.38.
SHUNT MACHINE.

the curved part *a b* of the characteristic nearer to or further from the point o.

A characteristic curve can be obtained for any two varying quantities which depend on each other, and for only two, as for instance, the current and potential; all other quantities (as for instance, the speed) should remain the same, except, of course, such quantities as the external resistance in this particular case, which must be changed to produce a change of current and potential. If it is desired to vary a third quantity, such as speed in this case, separate curves must be drawn for successive values of the speed.

Similar characteristics cannot be compared with one another, unless reduced to the same scales, for it is evident that two characteristics drawn to different scales, may be identical in appearance and size, but still represent totally different results.

The general characteristic for current and potential of a shunt machine, for different resistances, is shown in figure 38. Starting first with open circuit, that is with an infinitely large resistance, and, therefore, no current, the machine gives its maximum potential *o m*; with a gradually decreasing resistance the current increases and the potential falls slightly; it will continue to fall proportionately to the current as the resistant decreases, as far as the line *m a* is a straight line. At *a* the potential falls rapidly, and at *b* the maximum current is reached; by decreasing the resistance still more, the current and potential both fall until the resistance is zero, that is, until the machine is short circuited, when both are zero. This shows that there is a maximum current *o e*, which can be obtained from a shunt machine, and that the maximum potential *o m*, is when the machine is run on open circuit. It, furthermore, shows that if the armature can stand the maximum current *o e*, then no adjustment of the external resistance will injure the machine. This is not the case with a series machine which would soon be destroyed when run on too small a resistance, as seen from its characteristic. A shunt machine is never run in practice between the points *b* and *o*, because, as could readily be proved, the same output could be obtained from the same armature and frame with a much less expensive winding of the field magnets; it would therefore be very uneconomical, as far as first cost is concerned, to run a shunt machine at the part *b o* of the curve. The best machines are seldom run near the point *b*, being usually limited to a short part of the line *m a*. It would not be safe, therefore, to diminish the external resistance too much for fear

the maximum current $o\ e$ might be too great for the armature.

It will be noticed that the part $m\ a$ is nearly straight, and that, therefore, the potential falls regularly but slowly even for wide ranges of the current, and that if this line could be made to be horizontal the potential would be constant for the corresponding values of the current from o to $o\ f$. The inclination of this line is due to the fact that some of the electromotive force is absorbed in the armature itself to overcome its internal resistance, and that this amount increases with the current. If, therefore, the armature resistance be practically zero, there would be no fall of potential in the armature, and, therefore, this line $m\ a$ would be horizontal, in other words, the shunt machine would have a constant potential for greatly varying currents. This, however, would necessitate having either a very large armature or a very intense field, both of which add to the cost of a machine. Instead of avoiding this fall of potential, it may be neutralized or balanced by a simple combination of the two characteristics, figures 38 and 37, that is by a combined shunt and series winding. In figure 38 the potential at first falls in a regular proportion, while in figure 37, it rises in a regular proportion, therefore, by a proper combination of the two, their total action may be made to keep the potential constant. To do this the part $o\ a$ of the series curve should make only a small angle with the horizontal, as $o\ a$, figure 39, which is accomplished by using only a few series windings. This angle should be such that the increase of potential $f\ a$, figure 39, due to the series coils for any current, $o\ f$, should be equal to the fall of potential, $g\ a'$, due to the shunt coils, for which $m\ a'$ is the curve. The resulting action of the two will, therefore, be a constant potential for all currents from zero to a certain limit, $o\ f$. The characteristic for this compound machine will therefore be $m\ g$. How to proportion these two sets of coils to obtain this result has already been explained in chapter viii. It will be noticed

that the shunt characteristic in figure 39 curves downwards for currents greater than *o f*, and, that therefore, that for the compound machine *m g*, will also curve downward beyond *g*. This shows that a compound machine should be used only in such parts of the two characteristics, *o a* and *m a′*, as are nearly straight lines, for up to this limit only, can it be made to have a constant potential for different currents. It can readily be shown that the curving of the line *m g* at *g*, is due chiefly to the magnetic parts of a machine being nearly saturated; a compound

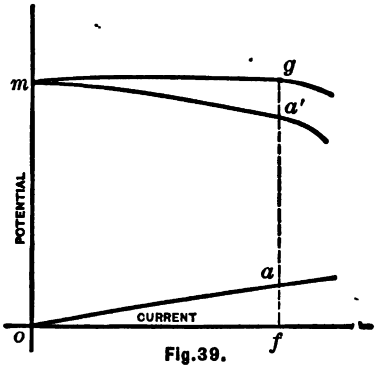


Fig.39.
COMPOUND MACHINE.

machine should therefore be run below the saturation point, as explained in chapter viii.

This leads to another and very important test which machines should be subjected to, namely, the test for saturation. This test is best made with temporary coils on the magnets, excited by a separate exciter the current from which can be varied between wide limits. It can also be made with the finished coils of a machine if the exciter has the proper potential for these coils. It can also be made with shunt or series machines by letting them excite themselves, but this is generally less satis-

factory, at least when it is desired to test the magnetic qualities independently, especially for series machines, as it is preferable and in some cases essential to have no appreciable current flowing in the armature.

To conduct this test, run the machine on open circuit at a constant speed and excite the magnets with currents varying successively from a very small current to as great a one as the magnet coils will stand. Set the brushes to the position of greatest potential and measure in each case

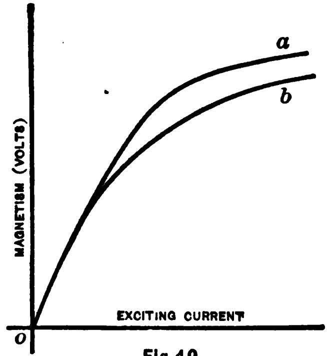


FIg.40.
SATURATION CURVE.

the potential at the brushes and the exciting current. This potential will then be a correct measure of the useful magnetism of the field for each case, while the exciting current will represent the cost of generating this magnetism. Lay off these values to any convenient scale and find the characteristic curve as shown in figure 40. It will generally be found that this curve resembles somewhat that of a series machine, figure 37, being at first nearly a straight line, showing that the magnetism increases rapidly with the exciting current; it then curves, showing that it no longer increases rapidly, or in other words, that the iron has become saturated. If this curving of the line is short and decided as in *o a*, it shows that the iron parts, including

cores, armature and yoke pieces, are all saturated about the same time, and are therefore properly proportioned as far as saturation is concerned. If, on the other hand, the curve is gradual with little or no straight part, as *o b*, it shows that some of the iron parts are saturated before the others. This, in some cases, as for compound machine, is objectionable, and should be remedied by increasing the iron parts of smallest cross-section, except when the machine is to be magnetized only as far as the curve is tolerably straight. Whenever the smallest cross-section of the iron parts is in the yoke piece, it should, of course, be remedied for any machine, but wherever, as is usually the case, it is in the cross-section of the magnet cores, or in Gramme ring machines, in the armature core, it is a question easily determined by trial calculations, whether the gain in the economy of magnetism obtained by increasing this cross-section, is justified by the additional expense of the increased amount of wire, the greater size, weight and resistance of the armature, etc., which this necessitates.

The end of the tolerably straight portion of this characteristic shows the limit at which magnetism is produced economically. Whether the machine (shunt or series, but not compound) should be run at a higher degree of magnetization can readily be determined by trial calculations; it evidently depends on whether the gain in the output of the machine is justified by the poorer magnetic economy (*i. e.*, lower efficiency of the machine) and the other objectionable effects of over-saturation.

Regarding the details of this saturation test, it is evident that a reliable voltmeter with a large range is required. It is not necessary to know the actual values of thereadings in volts, but it is necessary to know the relative values, that is, the voltmeter should either be one whose deflections are proportional to the potential, or else one in which the relative values of the deflections are known. If the voltmeter has only a small range of readings the machine may be run at different speeds, the speed being made lower as

the exciting current increases. To correct the readings for this change of speed, it is sufficiently accurate to assume that the voltage is proportional to the speed; this enables all the readings to be reduced to one speed, and applies therefor as well to the first method if the speed during that test has varied slightly. Instead of changing the speed to enable a voltmeter of small range to be used, successive resistances equal to that of the voltmeter may be used in series with it, thus reducing the readings to one half, one-third, etc.; but this is not to be recommended, as these resistances should not only be equal to that of the voltmeter, but also have the same self-induction, and unless they are carefully made it is difficult to make both the resistance and self-induction the same. If the voltmeter has no appreciable self-induction this objection does not apply. In the absence of a suitable voltmeter any indicator of small currents, as for instance a test galvanometer, may be used together with a suitable adjustable resistance, such for instance as the plug resistances box accompanying a Wheatstone bridge. Connect the resistances in series with the test galvanometer and adjust them so that any suitable deflection is obtained for the first reading. For any other potential adjust the resistances until the deflection is reduced to the same reading, then, knowing the resistance of the galvanometer, the potentials will be proportional to the total resistances, including that of the galvanometer and that in the resistance box.

If this saturation test is made with a shunt machine, that is, self-exciting, the speed should be somewhat greater than the normal in order to get the characteristic curve through the saturation point. For the same reason if the machine to be tested is series wound it should be tested for a greater current than the normal, but its speed may be much less, the external resistance being made smaller. It is preferable in this case to keep the armature current constant, and therefore vary the exciting current by variably shunting the current around the magnets.

In this saturation test the exciting currents multiplied by the number of windings in the exciting coils gives the ampere turns. These might have been laid off along the horizontal line in figure 40 in place of the exciting current, but as the number of windings is constant it would be equivalent merely to changing the scale of the diagram, but would not alter the relative proportions between different parts of the curve. If the coils used in this test are different from those to be used finally, it is necessary, of course, to reduce the exciting current to ampere turns, in order to eliminate the two unlike windings.

The numbers obtained from this saturation test will often be found to be of great assistance in designing other machines, or in correcting the proportions of a faultily constructed one. In chapter vii some of the applications of this data has been described, as for instance in correcting the proportions of an over-saturated frame. As described there, the exciting power of the coils (that is, the intensity of the field in the coil if there was no iron core) may be readily calculated approximately from the ampere turns and the cross-section of the core space. The constant thus obtained can be used as a guide in calculating the size of the cores or the ampere turns for other magnets in which the exciting power is to be of the same intensity. By calculating the total number of lines of force generated by the coils themselves (without iron cores) as described in chapter vii, and comparing this with the total number of useful lines of force in the armature field, found by calculation from a test (see chapter v and appendix I), constants may be obtained between the actual number of lines of force in the field, and the ampere-feet (that is, the number and length of the ampere turns) which generate the same. This constant serves as a valuable guide for determining the coil space, ampere-feet and ampere turns in designing other machines. There are, of course, other factors which enter into such calculations for new machines, for instance the quality of the iron, the magnetic resistance due to dif-

ferent lengths of cores, yoke pieces, etc., or to different air spaces between the field and the armature core; these will modify the calculations somewhat, and would complicate them very greatly if introduced, but as they are of secondary importance they may be neglected in approximate calculations, unless they are too widely different in the two machines. As in almost all other calculations which engineers have to make in designing any structure, a suitably chosen "factor of safety" will cover all such inaccuracies.

A careful study and analysis of the characteristic curves of a machine may often be the means of finding out faults

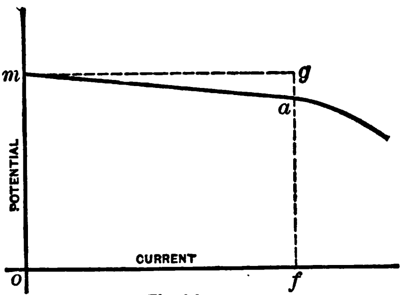


Fig.41.
SEPERATELY EXCITED MACHINE.

in the proportioning of the parts, or of indicating the most favorable conditions of running, and it is therefore to be recommended. Such curves are to the electrical engineer as the curves of a steam indicator cards are to the mechanical engineer, and there is no doubt that the latter have been the means of making a much more careful study of the steam engine.

The characteristics for the current and potential of the principal forms of machines, namely series, shunt and compound, have been shown in figures 37, 38 and 39, that for the less frequently used form, the separately excited

machine, is shown in figure 41. The exciting current being constant the magnetism of the field magnets will be constant; the potential will therefore be a maximum on open circuit, that is for the point *m*, when there is no current. As the current from the machine increases (for decreasing external resistances) the potential will fall slightly, which is evidently due to the internal resistance of the armature which consumes an amount of potential proportional to the current. The first portion, *m a*, of this curve is therefore straight and slightly inclined to the horizontal. When the armature current becomes very great, and especially when there are many armature windings, the counter magnetism of the armature will become great as compared to the magnetism of the field; this will, by diminishing the useful magnetism, cause the potential to fall more rapidly, and the curve will then no longer approximate to a straight line, as shown beyond the point *a*. As this counter magnetism generally necessitates shifting the brushes, well built machines are usually run with currents less than that for the point *a* where this rapid fall of potential begins. The fall of potential in the armature due to its internal resistance, as for instance *a g*, divided by the total electromotive sorce *g f* and multiplied by 100 will evidently give the percentage of energy lost in the armature. The continuation of curve *m a*, if it were possible to determine it, would ultimately meet the line *o f*, at a point which represents the greatest current which the machine gives on being short circuited, that is, when the potential at the poles is zero and the total electromotive force of the armature is absorbed in overcoming the internal resistance. This portion of the curve, although of interest theoretically, is of no use in practice.

Besides determining and examining the characteristics and the saturation curve of a machine, tests may also be made to determine other qualities, such as the counter magnetization of the armature, the shifting of the brushes, the exploration of the field, the magnetic leakage, the re-

sistance of the armature, heating of armature and field, etc., some of the results of which tests may be of use also for determining co-efficients which may serve as guides in designing other machines.

The effect of the counter magnetization of the armature may be ascertained by exciting the field with a constant current from some outside source and finding, with the aid of a voltmeter attached to the brushes, the position which the brushes must have to give the greatest potential first on open circuit and then for the greatest armature current; the amount of the change of the position of the brushes indicates the effect of the counter magnetization of the armature.

The effect of shifting the brushes may be determined by separately exciting the magnets and moving the brushes to successive positions to the right or left of the neutral line, measuring the potential in each case. This may be done for open circuit, for various current strengths, or various degrees of saturation; the same test may also be made with self-exciting machines.

To explore the field surrounding the armature, the following simple method may be used. Wind a single coil of one or more turns of fine wire around one part of the armature, over or next to one of the regular coils; connect one end of this coil to the shaft and the other to a little insulated metallic block fastened on to a wooden ring secured around the commutator, so that it acts as a single commutator bar for this little coil. Connect the terminals of a sensitive voltmeter or galvanometer to two brushes, and apply these to the two ends of this coil, one on the shaft and one on the wooden ring containing the metallic block. When the machine is running normally this little coil will generate an electromotive force, and therefore a current, which is proportional to the strength of that portion of the field through which it is passing when the brush is in contact with the block. The reading of the voltmeter or galvanometer will therefore indicate the strength of the field. By

moving that brush which is resting on the wooden ring around to successive positions on the circumference of the ring, the relative strengths of different parts of the field may be determined, showing whether it is unbalanced, and if so where and how much, also where the neutral line is, how wide the neutral space is, how great the magnetic lag is, etc. This test may be made first, when there is no current in the armature, and second, when the normal current is flowing, and it will then also show the effect of the counter magnetization of the armature. The results may be plotted in the form or characteristic.

The magnetic leakage may be found by simply exploring the space surrounding the machine and armature by means of a compass needle, the direction of which will indicate the direction and position of the lost lines of force.[1] To determine this leakage quantitatively, make a small, thin loop of one or more turns of fine wire, connect its terminals to a sensitive galvanometer having a moderately heavy needle so as to act as a ballistic galvanometer. When the machine is excited normally from an external source, the armature being at rest, place this little coil or loop to its full length in the space between the armature and the pole-piece, and withdraw it very rapidly; it will cut the lines of force and develop an electromotive force which will be proportional to the current or deflection of the galvanometer. By similarly moving this same coil through the lines of force of the leakage, its plane being always perpendicular to these lines of force, the deflections of the galvanometer will indicate the intensities of the leakage at different places, as compared to the intensity of the useful field, and will therefore give the percentage of leakage. If the actual useful number of lines of force per square inch of the armature field has been calculated as described from the induction in the armature, the actual number of lines of force per square inch of the leakage is readily determined.

1. See Appendix III.

The armature resistance may be measured by any convenient method of measuring small resistances, one of the best of which is to measure the fall of potential by the potentiometer method,[1] when a known current is sent through the armature, or to compare its resistance with a known resistance in series with it, by the fall of potential in each.[2] When a reliable volt and ampere meter are at hand, a very simple way of measuring it is to measure the potential first on open circuit while running, and separately excited, and then on closed circuit with a current which is not great enough to distort the field; the difference of the two potentials divided by the current will then be the resistance of the armature. If the exact length and diameter of the armature wire is known the resistance may be calculated, remembering that it is one-fourth of that of the whole wire.

To find the heating coefficients, measure the temperature by placing the bulb of a thermometer on the magnet coils after running normally for at least three or four hours, and covering the bulb with a little cotton; measure, also, the radiating surface of the coils and the number of watts dissipated in them; from these the coefficient may then be calculated as described in chapter viii. To measure the same for the armature it will be sufficiently accurate for all practical purposes to hold the thermometer in the air currents from the armature, between the pole-pieces, or else to place it on the armature immediately after stopping, and covering the bulb as before with cotton.

The efficiency of a machine is determined from the horse-power applied at the pulley, and the electrical power developed. There are several ways of stating this efficiency. The real or true commercial efficiency is the useful energy delivered in the external circuit divided by that applied to the pulley; this in the best machines varies from

1. See Flemings' Short Lectures to Electrical Artisans, page 129.
2. See Flemings' Short Lectures to Electrical Artisans, page 143.

80 per cent. to 91 or 92 per cent., and evidently takes into account all losses in the machine. The other efficiency, and the one often given by the makers, and called the total efficiency or efficiency of conversion, is the total electrical energy divided by that applied to the pulley, the total electrical energy being that in the external circuit, that lost in the armature and that lost in the field. It is evidently higher than the other, being sometimes as high as 97 per cent. The "economic coefficient" is the first efficiency divided by the second. In measuring the efficiency as well as in all cases in which it is necessary to measure the actual potential accurately, care should be taken in selecting the voltmeter, for if the voltmeter is in the form of a coil having considerable self-induction, the readings for the same potential will be quite different (as much as 25 per cent. it is claimed) according to whether the machine gives a steady current (as a unipolar machine or battery), or whether its current pulsates as in any machine with a commutator. The value of a reading therefore depends on the number of commutator bars and the speed. The most reliable method is to use a sensitive reflecting galvanometer with coils of few windings, calibrate it with a standard cell, and when using it with the high potentials of a dynamo add high resistances in the galvanometer circuit sufficient to get proper deflections. The constants of the instrument in volts per degree of deflection, will then be proportional to the total resistances in the galvanometer circuit in the two cases.

APPENDIX I.

Practical Deductions from the Franklin Institute Tests of Dynamos.

THE tests of dynamo-electric machines made in 1885 under the auspices of the Franklin Institute, are undoubtedly the most reliable and complete of all the impartial tests which have ever been made and published, and they therefore afford the practical electrical engineer an excellent opportunity to deduce proportions, dimensions and constants, to assist him in designing dynamos, especially as the machines which were tested are among the best that are made, and represent the results of tedious and expensive experimenting on the part of the makers, while, at the same time, they embody the improvements suggested by long and continued use of the machines in practice.

Dynamos have frequently been built by "guessing" at the proportions, constructing them, and then trying them to "see what they will give." If they then turn out (by chance) to give the electromotive force and current desired, the designer generally gets the credit for having made very correct "calculations;" while if they give, for some unknown reason, quite different results, the manufacturer has to be consoled with the statement that "it is not possible to calculate the parts of a dynamo."

If a machine is at hand which can be thoroughly tested and measured in all its parts, it is not difficult for a technical engineer, who is well informed concerning the principles and practice of dynamo building, to calculate the parts of another machine of the same type which will give a certain desired electromotive force and current slightly different from that of the first machine. But when the designer has no access to such a model machine, or if the

current and potential desired differ greatly from those of the model, it is difficult, if not quite impossible, to calculate with any degree of certainty the parts of a dynamo from the principles and laws of induction and resistance, without some practical constants and proportions, which can be obtained only from existing machines.

As an aid and guide in such calculations, a set of practical constants and proportions have been calculated by the writer from the valuable tests of the Franklin Institute. These constants will not only materially diminish the amount of "guessing" in designing machines, but it is believed they are sufficiently complete to enable a technical engineer to calculate all the electrical proportions of a well-designed cylindrical armature which is to give a certain required electromotive force and current. It is to be regretted that the data given in the Franklin Institute Report are not sufficient to enable a similar complete set of constants to be deduced for the field. A few of these may, however, be calculated, and they will materially aid in determining certain parts of the field. The calculations of armatures being based on induction and conductivity, the constants from one armature may be used in calculating others; but in the field this is not the case, as the relation between the exciting current and the magnetism produced depends very largely on the size, shape and proportions, of the coils and the iron parts, including the cores, the so-called neutral parts, pole pieces, etc., as well as on the quality of the iron. As these are so very different in different machines, the constants obtained from one would be of little use in determining the size of other fields, except, perhaps, the constants given below for the intensity and amount of the magnetism of the field. A careful and systematic builder of dynamos will in most cases run the armature, when completed, with its own field magnet frame with temporary, removable coils of known number of turns, on the magnets, in order to find, by regulating the current in these temporary field coils, how many ampere-turns

are required in the field to induce the desired electromotive force and current in the armature. From this number of ampere-turns any competent dynamo builder can readily calculate the proper windings of the magnets with all due accuracy.

Numerous theories of dynamo-electric machines have been advanced, but most of them are of greater interest to the mathematician and the physicist than to the practical dynamo builder. More attention seems to have been given to integrals, complicated abstruse fractions and formulæ for determining the presumably correct values for extreme impossible cases, than to simple, practical formulæ, by means of which tangible results may be obtained for the ordinary forms of machines. In some cases, formulæ based on physical theories have been suggested, which might have been of practical use if accompanied by the absolute and reliable values of certain constants usually represented by Greek letters, which enter as direct factors in the formulæ; but the values of these constants have either been omitted, or else have been given within such wide ranges that they cannot be used to any advantage in practice. They are sometimes of such a nature that they differ for each machine, thus necessitating the construction and testing of the machine before the values of the constants for calculating this particular machine may be determined; which is, to say the least, a very awkward way of applying a formula.

The writer has, therefore, set aside all abstruse theories of the dynamo, which have yet to stand the severe test of varied practical application, and has endeavored to deduce from the results given in the Franklin Institute Report some constants, or values, which are in such a form that they may be directly applied to the calculations of the armature and some parts of the field. The deductions of these constants are based only on the well-known laws of induction, and of mechanics, and as they are calculated from actual cases, they show what *is* done in practice, as distinguished

from what *might be* done according to some theory, provided the theory is correct.

The results contained in the accompanying table not only give the values which can be used in designing machines, but an attempt has also been made to determine the efficiency of separate parts; thus indicating under what circumstances the most advantageous proportions may be arrived at. Some proportions used in calculating the numbers given in the table were not contained in the report, and, therefore, had to be estimated, except where they were furnished to the writer by the kindness of the manufacturers. But the errors which may have been introduced by a slightly inaccurate estimate, are so small that they do not materially affect the results. Certain slight errors, or modifications, in some of the figures, or proportions, were not taken into account, as they cannot be determined; but they are of such a nature as to affect equally, or approximately so, all machines not differing too widely from the style of those tested. Among these is the self-induction of the armature; in well-built machines, like those tested in which the field is intense, the speed not too high, the number of commutator bars or coils large, and the number of windings per coil very small, the self-induction will be very small, and, therefore, the difference between the self-induction in these different armatures may be neglected.

In the table given below, the deduced constants have been accompanied by many of the proportions from which they were derived, as copied from the report, in order to show some of the principal proportions of the machines, and to give the conditions under which the constants have the values given. Numerous other values in the report might have been repeated here, but as it is presumed that any one can obtain the original report, they are omitted. The values chosen for the deductions were taken from that one of the full load tests in which the current and potential were nearest to the values given by the makers as the best working load.

The following assumptions were made, as the accurate data for deducing the same were wanting. The speed in the Edison No. 4 machine was not given in the report; that given here is the speed at which the makers say the machine is to be run, and it is assumed that the speed must have been very nearly this in the test. The percentage of the whole circumference of the armature which is embraced by the pole pieces was, in the Weston machines, assumed to be about 80%, as this was the proportion in some arc light machines of the same makers, which we understand have the same type of frame. The distance between the pole-piece projections was determined from this in the Weston machines. In the Edison machines the length of the pole pieces and the armature core, were deduced from the statement in the report giving the length of useful wire in a coil; it was assumed that by the term, "useful wire," was meant that which lies directly between the pole pieces and the armature core. In the Edison machines it was assumed that the length of the armature core was the same as that of the pole pieces; in the Weston machines, this was the case.

As the electromotive force induced in an armature is dependent upon the amount of magnetism passed through per second, the first questions in designing armatures are: How great may the velocity of the moving wire be? What must its length be? What must the intensity of the field be? etc.

The first of these, the velocity of the moving wire—commonly called the "conductor or inductor velocity"—depends on the distance of the active wire from the centre of the shaft, and on the number of revolutions of the armature. It may be calculated from the speed and the mean of the external diameter and the diameter of the core. In the accompanying table, the horizontal column *a* contains the external diameters, *b* the internal, and *c* the mean. From this mean value the circumference in feet was calculated, which, when multiplied by the speeds *d*, and reduced

to seconds, gives the inductor velocities in feet per second, in column *e*. From these values, it is seen that the Edison armatures have a higher velocity of the moving wire; also, that it is preferable to obtain the high inductor velocity by making the diameter as great as practical, rather than to increase the number of revolutions, as will be seen by comparing the small, high-speed armature of the Edison No. 4 with the large one of the Nos. 10 and 20.

To obtain a constant by means of which the length of wire may be calculated, the total electromotive force in volts which was generated, has been divided by the length of that part of the wire in which it is generated. This wire will be termed the "active wire" and, in these deductions, has been limited to that portion of the armature wire which lies directly between the pole pieces and the armature core. Strictly speaking this is not quite correct, as some induction does undoubtedly take place in some parts of the wire lying at the ends of the armature, and also in some of the longitudinal wires which are not directly between the armature core and the pole pieces; but the induction in both of these parts is presumably so small as compared to that in other parts, that it may be neglected, especially as the constants are to be applied to similar armatures, thus eliminating this error. The length of the active wires were calculated from the following proportions. Column *f* gives the number of coils or commutator bars; *g* the number of turns per coil, and *h* the resulting total number of turns on the armature. The proportion of these coils which are active, is calculated from the distance between the pole piece projections, column *i*, and the circumference determined from the diameters in column *a*; the ratio of this is given in column *j*, in percentage of the circumference of the armature which is active; this will also represent the percentage of the number of windings which are active. Column *k* gives the length of a pole piece in inches, which is the same as the length of the armature core. From these the total length of the

active wire in feet can be calculated, remembering that every turn of wire on the armature represents twice the length of the pole piece; but as the two halves of the armature wires are in multiple arc only half of this induces the whole electromotive force. The total electromotive force in volts, given in column *l*, is then divided by this half length of active wire in feet, giving the induction in volts per foot in column *m*. As this induction is slightly different in different positions of the wire with reference to the pole pieces, these results give the mean value. They show that the induction is considerably higher in the Edison than in the Weston machines; also, that it is very nearly the same in all the Edison, and nearly the same in the three Weston machines.

These constants are dependent on the velocity of the inductor, for it is evident that if the latter were higher the induction would be increased. In order, therefore, to properly compare these constants, it is necessary to eliminate the velocity by dividing these figures by the velocities in column *e*, thus giving the volts per foot which would be induced (in the respective fields) at a uniform velocity of one foot per second. This is given in column *n*, and shows the number of volts induced per foot for an inductor velocity of one foot per second. These may be compared with each other as the velocities are the same. They show that at the same velocity the induction is better in the Edison than in the Weston machines; also, that the values agree very closely for all the Edison, except for the No. 4 machine, which may possibly be attributed to the number assumed for the speed, which was not taken in the test. For the Weston 6 M it is lowest, which is no doubt due to a less intense field.

The next question which naturally arises is, what was the intensity of the field in these machines. This may be determined as follows: We know that a volt is 100,000,000. times the unit of electromotive force in the absolute system, and also that one absolute unit of electromotive force

is generated when a wire cuts lines of force at the rate of one per second; therefore, one volt is induced if a wire cuts 100,000,000. lines of force per second. As we know the number of volts in one foot (column *m*) in these machines, and also the number of feet moved through in one second (column *e*), we can readily calculate the intensity which the field must have had to induce that number of volts in one foot. To illustrate this, suppose the velocity was one foot per second, and that the induction was one volt per foot at this velocity, then it is evident that the surface moved over by one foot of wire in one second, that is, one square foot, must contain 100,000,000. lines of force; or, if the induction was two volts per foot, there must be 200,000,000. lines of force in this space, as this number must have been cut per second to generate two volts. Dividing this number by 144, will give the mean intensity of the field in number of lines of force per square inch. These figures are given in column *o*. They show that with one exception, all the Edison machines have very nearly the same intensity of field; also, that it is somewhat lower in the Weston, especially in the 6 M machine; but, as will be seen, it is more economically obtained in this one, which indicates that it was probably not over saturated.

These values might also have been obtained by multiplying those in column *n* by 100,000,000. and dividing by 144, which is equivalent to multiplying them by 694,444. This will be seen by considering the principles of the deductions.

The total useful amount of magnetism in the whole field is evidently the intensity per square inch multiplied by the size of the field in square inches. As the intensity has been calculated from the amount of induction, the amount of magnetism thus obtained does not include the leakage of the magnetism, that is, those lines of force which are not cut by the armature wire, it therefore represents the useful magnetism only. The same lines of

force which enter the armature at one pole piece pass through it to the other pole piece, and therefore the total number of lines of force is the intensity multiplied by the curved area of one pole piece. These figures are given in column *p*, and are deduced from columns *o*, *a*, *j* and *k*. The magnetism increases with the number of volt-amperes which the machine generates.

This amount of magnetism is generated at the expense of a certain quantity of electrical energy in the field magnets. In order to get some approximate values for calculating roughly how much electrical energy will be required for generating, in practice, a certain amount of magnetism in similar fields, the figures in column *p*, may be divided by the amount of energy in volt-amperes, which was required in these cases to generate the respective fields. In the report the figures in column *q*, are given, which are the energy in horse-power consumed in the fields. Unfortunately the resistance of the field without the regulator box was measured only in one machine, so that the energy given here represents more than that used in the field magnets themselves, thus introducing an error in all the deductions made from these values. It is presumed, however, that at full load the resistance in the box was not large, so that the error will probably be small. Reducing this energy in the field to volt-amperes and dividing it into the amount of magnetism, gives the number of useful lines of force generated per volt-ampere in the field. These are given in column *r*. As they depend on so many different proportions of the parts of the field and magnet coils, and also in a measure on the armature, they might vary considerably for different types of field magnets, and can, therefore, be used only in making rough preliminary calculations. They agree tolerably well for these fields, except for the Weston 6 M, which is evidently better proportioned than the others. As these figures are the ratio of that which is produced to that which is required to produce it, they may be said to represent the *relative* efficiencies of

the different fields, in which sense they represent no absolute efficiencies, but serve simply to compare the efficiencies with one another. In the Edison machines we believe wrought iron alone is used, while in the Weston both wrought and cast iron were formerly used together, and we presume were used in these machines also. Possibly the iron in the field of the Weston 6 M machine is not over saturated, which may be the reason of its high efficiency of field.

The wires of the armature being wound repeatedly around it, pass through the same field a number of times, thus utilizing the same field in one revolution for successive inductions in the same wire. This number of turns, as given in column *h*, multiplied by column *j*, may, therefore, be said to represent the economic use of the field; it does not follow, however, that the best armature is the one having the greatest number of turns on it, as it is quite the reverse, other more important considerations, such as self-induction, sparking, etc., require that the number of turns of wire be as small as practicable.

In deducing the number of volts per foot, only the active wire was taken into consideration. In designing armatures it is therefore necessary to know what the proportion is between the active and the total length of the wire, for if the active length is determined first from the number of volts to be generated and the induction per foot, we must find what the total length is in order to determine the resistance or cross-section of the wire. This proportion of active to total length will evidently depend on several dimensions of an armature, and will, therefore, vary somewhat in different machines. For these machines it was determined as follows: column *s* contains the mean length of wire in one turn (where several smaller wires are in parallel they were considered as one); this multiplied by the number of coils in column *f*, gives the total lengths in column *t*; these divided into the active length in column *u*, give the percentages in column *v*. From the latter it will

be seen that the economy of the wire is considerably better in the Edison than in the Weston, and that it is best in the Edison No. 20, the proportion between the length and diameter of the armature being greatest in this one. Most of the proportions from which these percentages have been deduced were given by the makers.

The density of the current in the armature wire can be determined from the diameters of the wire in column *w*, the number of wires in parallel in a coil, in column *x*, and the total current in the armature in column *y*. Dividing the latter into the double area of cross-section of the wire in square mils, or the double sum of the cross-sections of the parallel wires, gives the number of square mils per ampere in column *z*. These numbers vary somewhat with the current and with several other proportions; they should, therefore, be used only as a general guide, or for making preliminary calculations. The best method for determining the cross-section, is to find the resistance from the amount of energy which is allowed to be lost in the armature, which together with the total length of the wire as determined from the induction per foot, etc., gives the required cross-section.

The percentage of energy in the armature as taken from the report, is given in column *A*. Those in which the loss is least, Weston 6WI and Edison No. 10, have the greatest area of cross-section of wire per ampere (column *z*), while the one in which the loss is greatest, Weston 7 M, has the least cross-section per ampere. This relation does not necessarily exist between them all, as the percentage of loss depends also on the induction per foot of wire, and therefore on the length of the wire.

The relative efficiencies of these armatures, as inductors, may be seen from the figures in column *C*. The efficiency as an inductor, apart from that as a converter of energy, is greater the larger the total amount of electrical energy induced (column *B*), and the less the amount of wire necessary to effect this induction; it may, therefore, be expressed by the quotient of the two. The figures in column

C have, therefore, been calculated by dividing those in column *B* by the lengths in column *t* and by the double area of cross-section determined from columns *w* and *x*, the decimal point being changed to reduce them to a convenient form. By themselves these figures represent nothing, but by comparing them with one another they show which of the armatures are the best proportioned as inductors. They show that the Edison are considerably better proportioned than the Weston. The most efficient armature is, strange to say, the smallest one, Edison No. 4, which is no doubt due to its having the most intense field (column *o*), the highest speed (column *d*), and almost the smallest cross-section of wire per ampere (column *z*); this higher efficiency is, however, obtained at the expense of the efficiency of the field, as will be seen from column *r*; the useful commercial efficiency of the whole machine is, therefore, below the average, as seen from column *D*. Next to this armature, in point of efficiency as an inductor, is the largest one, Edison No. 20; its high efficiency is no doubt due to the great intensity of field (column *o*), the very small amount of wire on the armature (column *t*), the relatively high inductor velocity (column *e*), the large proportion of active wire (column *v*), and the comparatively small cross-section of the wire, per ampere (column *z*). The field of this machine has next to the highest efficiency as seen in column *r*, and therefore, as might be inferred, the machine has the best useful commercial efficiency of all of those tested, as seen in column *D*. It may be interesting to mention here that in this machine which has the best efficiency, the armature wires cut the field less frequently than in any other, as seen from the number of turns in column *h*.

Another proportion which may serve as a guide in designing armatures, is the relation between the outside diameter of the armature and the diameter of the core, or what amounts to the same thing, the percentage of the external diameter which is taken up by the wire on both sides. These figures are given in column *F*, and are

obtained by dividing twice the depth of the windings given in column *E* by the external diameter in column *a*. This is greatest in the smallest armature, Edison No. 4, showing another disadvantage of small armatures ; it is least and therefore best, in the Weston 6 M, which may partially account for the economic field shown in column *r*, as the latter depends on this non-magnetic space.

A few other proportions may be deduced from the data given. One of these is the proportion of the distance between the pole-piece projections and the distance, between the pole pieces and the armature core. This proportion should evidently be as great as practicable. The figures are given in column *G* and are obtained from columns *i* and *E*, allowing about $\frac{1}{16}$ of an inch for clearance on each side. It is greatest for the largest machine, Edison No. 20, which may partially account for its economic field in column *r*. The reciprocals of one-half of the numbers in column *G* may be said to represent approximately the intensity of the leakage of magnetism, as compared to the intensity of the useful field at these places, as the lines of force have the choice of these two paths. But this will be only a rough approximation as a field is always more intense at points or sharp edges.

Another useful proportion is the relation between the length and diameter of the armature core, as deduced from columns *k* and *b*. It is given in column *H*, which shows by comparison with column *v* the advantage of a long armature. The Weston machines appear to be quite uniform in this respect, the length being almost twice the diameter.

Column *I* gives the relation between the length and diameter of the bearings.

Column *J* gives the electromotive force between two neighboring commutator bars. If this is great enough to maintain an arc across the insulation of the commutator bars (about 20 volts) there is danger of starting the well-known flash, encircling the whole commutator, if the brushes should be misplaced sufficiently far to start the

arc. It will be seen to be far within the limit of 20 volts in all of these machines.

The Edison Nos. 10 and 20 machines, afford a good opportunity to compare two armatures of different lengths, but having all the other sizes and proportions alike, including the number of windings, size of wire, depth of winding, etc., only that in the one three wires are connected in parallel, and in the other, two; and that in the No. 20 the distance between the pole-piece projections is greater, making a difference of about 10 per cent. in the number of active wires in favor of the smaller one. The chief gain of the long armature is seen in column v, in which it has the highest percentage, which partially accounts for the efficiency in column C, and the consequent commercial efficiency in column D.

The subject of self-induction of the armature was purposely omitted here, partly because insufficient data are given in the report to make any practical deductions regarding it, but principally because it is presumed that the self-induction in such armatures as these, with very few turns, is so small that it may be neglected in such rough values as have been deduced here. It is to be regretted that the resistance of the field coils without the regulator box was not measured in each case, in order that the effect of the self-induction of the field coils in increasing the apparent resistance could be calculated, and its relation to the number of pulsations or commutator segments determined. In only one case was the field resistance measured alone, and from this a calculation shows an increase of resistance of less than one-tenth of one per cent., and, therefore, probably less than the allowable error in measurement.

The fact that the Edison Nos. 5 and 20 machines gave way in the armature insulation, will not lessen the value of these deductions to the designer of dynamos, as this was presumably a defect in the details of construction and not in the proportion of parts.

The test of the 20-light machines were marked unofficial

in the report because the preliminary run of ten hours was not on full load ; but they are no doubt sufficiently accurate for the deductions of the approximate values in the table.

The deductions made here are not for the purpose of comparing the commercial value of these machines, as it has been shown in the tests that they are practically equal electrically. The most important consideration in this respect would be the cost of the machines and the cost of maintenance and attendance, which cannot be considered here.

For the benefit of any one not familiar with these machines, it may be added that they are all simple shunt machines, with cylinder armatures.

The full report of these tests will be found in the supplement to the *Journal of the Franklin Institute*, November, 1885.

In conclusion, it may be said that the values deduced in the table may not be free from small errors, as great accuracy was not possible in all cases, owing to the want of some few detail dimensions ; moreover, great accuracy has no particular value in such general deductions as these.

		Edison No. 4.	Edison 5 or *T.*	Edison 10 or *S.*	Edison 20 or *H.*	Weston 6 *M.*	Weston 6 *W I.*	Weston 7 *M.*
External diameter of armature in inches.....	*a*	7.063	7.875	10.625	10.625	8.031	8.250	9.375
Internal diameter or diameter of the core....	*b*	6.250	7.063	9.688	9.688	7.387	7.410	8.595
Mean diameter in inches..................	*c*	6.657	7.469	10.156	10.156	7.709	7.830	8.985
Speed in revolutions per minute.............	*d*	1600.	1400.8	1208.6	1092.1	1114.9	1257.6	1043.5
Mean inductor velocity in feet per second....	*e*	46.5	45.6	53.6	48.2	37.4	43.0	41.0
Number of coils or commutator bars...	*f*	50	50	64	44	72	56	64
Number of turns per coil.....................	*g*	2	2	1	1	2	2	2
Total number of turns on armature......... ...	*h*	100	100	64	44	144	112	128
Mean distance between pole-piece projections in inches.....................	*i*	2.69	2.313	3.50	4.88	2.52	2.58	2.94
Active part of circumference of armature in per cent. (approx.)........................	*j*	76	80	80	71	80	80	80
Length of pole piece or armat. core in inches.	*k*	12.	13.	16.5	29.5	14	14	16.5
Total E. M. F. in volts.........................	*l*	131.91	131.5	129.35	129.60	127.17	136.22	165.58
Mean induction in volts per foot.............	*m*	1.733	1.515	1.838	1.687	.948	1.304	1.175
Volts per foot for 1 foot per second..........	*n*	.0373	.0332	.0343	.0350	.0254	.0303	.0287
Mean intensity of field in lines of force per square inch...	*o*	25,900.	23,000.	23,800.	24,260.	17,630.	21,000.	19,900.
Amount of magnetism in field in lines of force.	*p*	2,660,000.	3,090,000.	5,250,000.	8,600,000.	2,420,000.	3,042,000.	3,860,000.
Energy in field in horse-power................	*q*	.394	.401	.675	.862	.207	.402	.498
Useful lines of force per volt-ampere in field, (relative efficiency of field)...	*r*	90.2	103.1	104.1	133.5	161.1	101.5	103.7
Length of wire in one coil in inches...........	*s*	92.	102.	68.	98.	154.	151.	160.
Total length of armature wire in feet (parallel wires considered as one)..................	*t*	383	425	363	359	924	705	858
Available active length in feet	*u*	152.0	173.4	140.8	153.6	268.8	209.0	281.6
Percentage of same, which is active...........	*v*	40	41	39	43	29	30	33
Diameter of naked armature wire in inches..	*w*	.148	.180	.199	.199	.141	.190	.175
Number of wires in parallel...................	*x*	1	1	2	3	1	1	1
Total current in armature...	*y*	84.42	103.81	205.50	392.42	72.84	100.60	128.16
Square mils of cross-section per ampere......	*z*	407	492	606	475	428	562	374
Percentage of energy in armature....	*A*	3.70	4.65	3.12	3.39	5.43	3.09	5.59
Total electrical energy in horse-power.......	*B*	14.93	18.23	35.67	68.25	12.43	18.39	28.47
Relative efficiency of armature as an inductor.	*C*	11.33	8.44	7.00	10.17	4.32	4.62	6.94
Useful commercial efficiency of machine.....	*D*	88.38	89.76	89.70	91.90	87.38	90.21	89.92
Depth of winding in inches..........	*E*	.407	.406	.469	.469	.322	.420	390
Percentage of diameter taken up by windings.	*F*	11.5	10.3	8.88	8.83	8.02	10.2	8.82
Distance between pole-piece projections divided by depth of windings and clearance	*G*	5.0	4.4	5.9	8.2	5.65	4.75	5.72
Ratio of length to diameter of armature core.	*H*	1.9	1.8	1.7	3.0	1.9	1.9	1.9
Ratio of length to diameter of bearings.......	*I*	4.2	4.3	4.1	4.1	4.2 & 3.6	4.2 & 3.6	3.8 & 4.3
Volts per commutator bar.....	*J*	6.7	6.25	4.9	7.2	4.2	5.9	6.1

APPENDIX II.

The So-called "Dead Wire" on Gramme Armatures.

The question whether the wire on the inside of the Gramme ring armature and on the ends of a cylinder armature, is active or inactive, has been discussed at great length in the last few years, but apparently without leading to any definite and indisputable conclusions. Recent publications show that some authorities still appear to believe that for some theoretical reasons the wire on the inside of a Gramme ring is as active as that on the outside. The writer has therefore made a simple and conclusive experiment which appears to prove beyond question, whether this wire is active or inactive.

The question is not one which is of interest merely from a theoretical point of view, but it bears directly on important points in the construction of machines, such for instance as placing a magnet in the inside of a Gramme ring, or making a cylinder armature of square section instead of oblong.

The two theories which explain the generation of electromotive force by moving a wire near a magnet, may be briefly summarized as follows: If a loop of wire, *a b c d* in figure 1, be revolved about its axis in a magnetic field between two opposite poles, an electromotive force will be generated in the direction as shown. The first and older theory, sometimes termed the theory of threading lines of force through a loop, explains the induction of an electromotive force, by saying that the number of lines of force which pass through this revolving loop is always either increasing or decreasing, and that this increase or decrease in the number of lines of force threaded through the loop generates electromotive force. According to the second and

newer theory, generally termed the theory of cutting lines of force, an electromotive force is generated when a wire cuts lines of force; the induction therefore takes place in the two parts *e f* and *g h* of the loop *a b c d*, and only in those parts, as the remainder of the loop does not cut lines of force.

It will be seen that these theories, as stated, do not conflict, both may be, and undoubtedly are, correct as far as

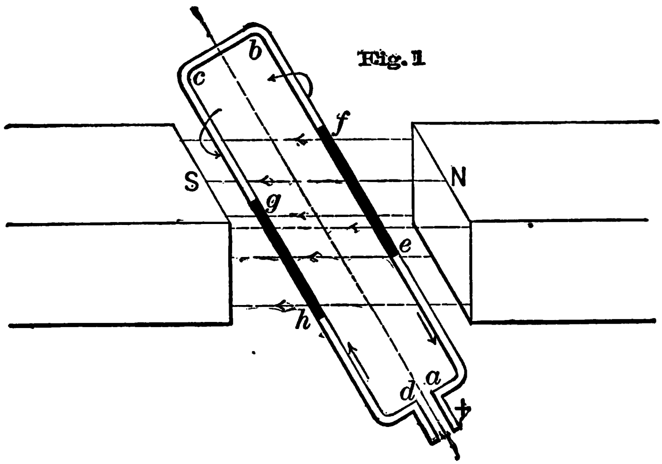


Fig. 1

they go. The second theory is, however, by far the more satisfactory as it tells us precisely where the induction takes place, and where we must endeavor to place the wire of a loop or coil in order to render it active. The first theory, referring only to the loop in general, leaves us to believe that the loop must be considered as a whole, and that, therefore, all parts of the wire forming the loop are of equal importance in the generation of electromotive force, that is, they are all equally active. The theory does not state, directly, that all parts of the loop are equally active.

but it leaves one to infer that this is the case; it is this interpretation of the theory which, it is claimed, proves that that part of the wire which is on the inside of the Gramme ring and on the ends of a cylinder armature is as active in the generation of electromotive force as the other parts of it.

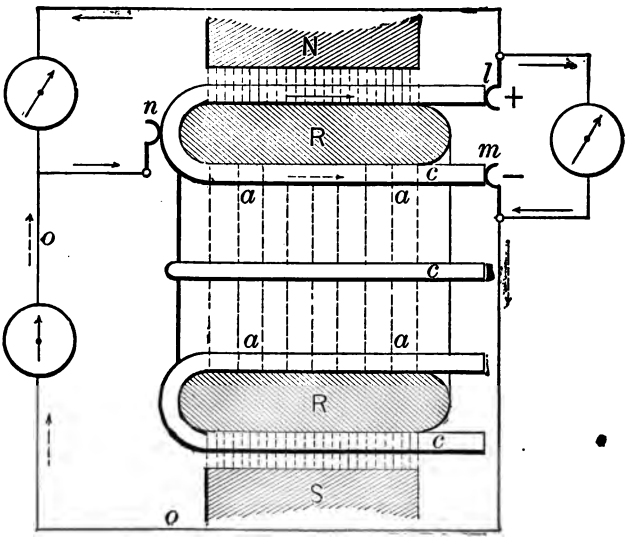
This interpretation of the older theory necessarily conflicts with the theory of cutting lines of force; both cannot be correct. We believe that the older theory is generally interpreted in this way; if not, and if the induction is not the same in all parts of the loop, then the theory is not sufficiently complete or exact to enable us to properly design dynamos, as it does not tell us where the induction does take place. According to the older theory it is the loop *a b c d* as a whole, which generates the electromotive force, the theory does not tell us what parts, if any, of the loops are superfluous. On the other hand, the second theory states that the induction takes place in the parts *e f* and *g h*, and that the rest of the loop is useless as an inductor, it serves merely as a conductor or collector of the currents, and should, therefore, be made as short as possible.

In order to prove conclusively which of these two conflicting statements is wrong, without the use of any abstruse theoretical deductions, the writer made the following simple experiment with a view, more particularly, of finding out whether the wire on the inside of a Gramme ring was active in generating electromotive force, or whether it was mere dead resistance, acting only as a conductor.

The core of a Gramme ring was wound with a number of coils, each one consisting of only one turn of a wire, as shown in figure 2, in which R R is the core of the ring, shown in vertical cross-section; N, S, are the two poles of the field, and *c*, *c*, *c*, are three of the coils. Each coil consisting of one turn, is insulated from all the others and has its two ends, *l*, *m*, bare and not connected with

any of the others; each coil has its insulation scraped off at the bend *n*. Three fixed brushes, *l*, *m*, *n*, were fastened to the frame of the machine so as to touch these three parts of each coil as it passed by them. The field was excited by another machine and the armature was made to revolve rapidly. In applying a test galvanometer to the

Fig. 2



brushes *l* and *m*, as shown, there was a strong current flowing in the direction indicated, showing the action of one coil of a simple Gramme armature. In order to find out whether this induction took place equally in all parts of the loop or coil *l n m*, according to the older theory, or whether it took place only in that part *l n* which cuts lines of force, the test galvanometer was placed first between

the brushes l and n, indicating a current, as shown, in the same direction as before, the current indicated by it being in this case only that which was generated in the half of the loop l n, the other brush m having first been removed. The brush l was then removed and the galvanometer placed between the brushes m and n, in which case it indicated no current whatsoever, showing conclusively that there was no electromotive force generated by that portion (m n) of the loop which was in the inside of the ring. According to the older theory it ought to assist in generating the electromotive force manifested at l and m, as it forms part of the loop l n m through which the lines of force are threaded from the pole-piece N to the core R. The experiment, however, showed conclusively that it did not generate electromotive force, that all the current which flowed from l to m through the galvanometer was generated in the part n l, the other part, n m, acting merely as a dead resistance to conduct the current from the end n of the active wire to the brush m. According to the newer theory the part l n is the only portion of the loop which cuts lines of force, and should, therefore, be the only one in which induction takes place,—which the experiment has shown to be the case. The part m n being shielded from the magnetism by the iron R, does not cut lines of force and is, therefore, dead resistance. This, therefore, applies equally well to the wire at the ends of cylinder armatures.

This shows conclusively the correctness of the theory of cutting lines of force and the fallacy of the older theory as interpreted above. But aside from theories, it shows that, as there is no induction in the part m n, it is preferable to dispense with it if practicable, for instance, by bringing it around on the outside of the ring on the opposite side, thus making a cylinder armature of it, or by rendering it active by creating a field in the inside of the ring with an additional pair of pole pieces and magnets. The experiment also shows that if it were not for other reasons the best form for a cylinder armature, as far as relates to dead

wire, would be to have it very long, and very small in diameter.

A second experiment was then made to still further prove the correctness of the theory of cutting lines of force. The field was made very intense so as to over-saturate the core R R, thus causing some lines of force, *a a*, to leak through the air space in the inside of the ring; such conditions no doubt often exist in Gramme armatures, the iron in the core of the ring being frequently much too small in cross-section. In again applying the test galvanometer at *l* and *m*, or at *l* and *n*, the same results as before were obtained, but on connecting it with *m* and *n*, it indicated a current in the direction shown by the dotted arrows, which is in the *reverse* direction, around the coil, to that induced in *n l*, and therefore tends to neutralize it. This is readily explained by the newer theory, as the wire *m n* cuts the lines of force *a a* and, therefore, must generate a current in the direction shown. The older theory seems to fail completely to account for this current, for, according to that theory it ought to be in the other direction. The only way to account for the current by this theory, appears to be to consider the loop as being formed by the wire *m n* and the test galvanometer circuit. But this fails to explain why the difference of potential exists at *m* and *n* when there is no galvanometer circuit, a fact which can readily be proved.

As the wire on the inside is thus shown to be dead, it might be inferred that the advantage of placing a second pole-piece and magnet in the inside would be very great, doubling the number of volts generated, as it doubles the active length of wire. But this is by no means the case, provided the machines are in both cases well proportioned. The reason is as follows. For the same armature, the number of volts generated depends only on the total number of lines of force cut, provided the speed is the same. If the armature core is saturated by the ordinary form of pole pieces, it is not possible to economically increase to any

great extent the number of lines of force which enter it; a second pole-piece may be placed in the interior and will distribute the field over a larger surface of the armature, but it cannot add much more magnetism because the core, being already saturated, cannot be forced to take many more lines of force. It therefore appears that any such gain due to interior pole pieces would be limited to the cases when the armature core is not saturated by the external pole pieces. But there is apparently no reason why this case should occur, as it is always possible to saturate the small cross-section of the ring by the large pole pieces on the outside.

We are informed by good authority that the theory of cutting lines of force assumes that the number of lines of force which follow the ring from pole to pole is proportional to the area exposed to the pole pieces. We are unable however to find anywhere, such a statement as a part of this theory; on the contrary it can readily be proved that this general assumption is not correct in many cases. As long as the iron of the ring is below saturation then it is true that the induction will increase about in the same proportion as an increase in the size of the pole-piece area, provided the intensity per square inch remains the same, for it is evident that in this case the total number of lines of force, that is, the capacity of the magnets, will have to be increased proportionally. But as soon as the ring is saturated, then an increase in the size of the pole pieces (of the same intensity per square inch) will no longer increase the number of lines of force proportionally. In this case, which is the more common, the above assumption is, therefore, not correct. It is understood, of course, that if the area of the pole pieces of the same intensity be doubled for instance, the capacity of the magnets for generating the magnetism must be doubled, as there are then twice as many lines of force.

This subject of interior pole pieces was referred to in some of the writer's earlier articles in which it was shown

that the electromotive force will be increased proportionally with an increase in the number of lines of force passing into the core, and that these lines of force may be increased by increasing the size of the pole-piece surface of the same intensity, provided the iron in the magnetic circuit is not over-saturated, in other words if the cross-section of the iron (including the core of the armature) be increased in proportion to the number of lines of force. For instance, suppose the cross-section of the core of the armature to be doubled, and the number of lines of force entering it be doubled either by doubling the area of pole pieces of the same intensity, or by doubling the intensity and keeping the area the same, then it is evident that if the speed with which the wire passes through the field remains the same, the induction in volts will be twice as great, and as the wire is not necessarily doubled in length the induction in volts per foot will be greater than it was before.

As the small core of a Gramme ring can generally be saturated by pole pieces on the outside, the advantage of interior pole pieces must not be looked for in this direction. The chief gain seems to be in increasing the area of the non-magnetic space between the pole pieces and the armature core, and thereby diminishing materially the great magnetic resistance which this space offers to the lines of force. According to S. P. Thompson, the magnetic resistance of air may be 20,000 times that of the iron, which, if correct, will show the great importance of making the magnetic resistance of this space as small as possible by increasing its area and diminishing its depth or thickness. Kapp[1] states that the magnetic resistances of air and iron (at low magnetization) are as 1440 to 2. Although this is much lower than the figure given by Thompson, it shows that it is highly improbable that it may happen that the resistance of the air space between the pole and the armature ring will be much less than that of the ring itself,

1. Proceedings of Society of Telegraph Engineers and Electricians, Nov. 11, 1886.

except perhaps in abnormally proportioned machines with a very small amount or a poor quality of iron in the ring. In such poorly designed machines the advantage of interior pole pieces would be less.

This advantage of interior pole pieces, therefore, lies in the economy of the magnetism, but as this magnetism requires for its generation only from 2 to 10% of the total energy of the machine, the advantage is merely in the reduction of this small fraction.

There is a disadvantage in having an interior pole-piece which in some cases may be so great as to more than outweigh the advantages. The speed of the wire on the inside is necessarily less than that on the outside; with small thick rings this difference is very great being sometimes as great as 40 to 50%. In that case if the interior pole-piece merely re-distributes lines of force by taking some from the outside surface and leading them into the ring on the inside surface, it is evident that it will do more harm than good, as many of the lines of force will then be cut at a less speed, and therefore generate less potential.

Another disadvantage lies in the fact that the two interior pole pieces may, in the case of smaller rings, be quite near to the iron or steel shaft, in which case many of the lines of force will leak directly across from one to the other through the shaft, and as these are not cut by the wire on the armature, they are wasted.

One way of rendering the inside wire active is to place a short thick fixed magnet in the inside of the ring, the poles of which are of like polarity to those on the outside. With such a machine the following experiment might at first appear to be a convincing illustration of the great advantage of such an interior magnet, but upon closer examination the apparent advantage will be found to have been due to other causes. Let the machine be run with both external and internal magnets excited and let its output be measured. Then let another test be made but without exciting the interior magnet; it will be found to generate

very much less electrical energy, thus apparently showing an advantage in favor of the interior magnet. But it will be noticed that when the interior magnet is not excited many of the lines of force from the external magnets will pass directly across the ring and through this dead magnet, which then acts as a sort of magnetic short circuit to the poles of the ring ; many of the lines of force will then no longer be threaded through the coils on the ring, which will therefore generate much less potential. Or, according to the other theory, the wire on the inside will then cut lines of force which have the wrong direction, and will therefore generate a potential in the *reverse* or opposing direction similarly to the case of the wire *m n* figure 2, which, when the core is over-saturated, cuts the wasted lines of force *a a* which, having the wrong direction, generate an opposing electromotive force as shown. The output of the machine in the second case will therefore be the difference of two opposing electromotive forces. The interior magnet therefore does harm when not excited, the machine would in this case generate more potential if the magnet were removed altogether. The proper way to make such a comparative test would be to test the machine first with the interior magnet excited and then with this magnet removed altogether. Any difference may then be safely attributed to the interior magnet.

The experiment just described is only one among many which show how easy it sometimes is to mislead, by striking results, the minds of people who prefer to trust to their own powers of observation rather than to accept the opinion of a technical engineer.

APPENDIX III.

Explorations of the Magnetic Fields Surrounding Dynamos.

DURING the Electrical Exhibition at Philadelphia, in 1884, the writer had occasion to examine the large Edison dynamo, commonly known as "Jumbo," with a view to find what disturbing effect, if any, the iron of the direct coupled steam engine had upon the distribution of the magnetism of the two pole pieces, it being attached to one of them. The examination was directed to finding the position, polarity, and approximately the intensity, of magnetic poles on different parts of the engine and pole pieces. By the somewhat strange behavior of the exploring needle, the writer's attention was drawn to the peculiar distribution of the magnetism around the yoke piece and parts of the coils of the dynamo itself where it was apparently not affected by the engine. The peculiar results obtained in some parts led to a similar examination of other machines at the exhibition with a view to making diagrams of the magnetic fields surrounding the dynamos by plotting the direction of the external lines of force. The resulting diagrams were not only interesting but may also prove to be instructive to designers and builders of dynamos, as they show clearly and conclusively the nature of the invisible field surrounding the different parts of the magnets; and as a large part of this field is leakage or wasted magnetism, they show how frames should and how they should not be constructed with reference to magnetic distribution.

The tests were made as follows. The exploring needle, which may be termed a "magnetoscope" or indicator of magnetism, as distinguished from a "magnetometer" which measures the quantity, was an ordinary short, light, compass needle, strongly magnetized and loosely

supported on a pivot. While the dynamos were running and the magnets fully excited, this needle was moved about in the space surrounding different parts of the magnets and the machine frame. If the case containing the needle be turned so that the needle is always perpendicular to its pivot, thus allowing it to turn as if on a ball and socket joint, the needle will take the direction of the lines of force in this space. By moving it systematically all around the different parts of the machine, and by plotting the direction of the needle on outline drawings of the machine, the directions of the lines of force may be readily indicated. To explore the curved paths of the lines of force the needle may be held near to any particular part of the frame and then moved continually in the direction in which the farther end points, that is, as the direction of the needle changes the direction in which it is moved must be changed so as always to conform with that to which the needle points. The path which it describes will then be that of the particular line of force. In this way the curvature and the two terminals of an external line of force can readily be determined and plotted with all due accuracy, as the needle is always a tangent or short cord to that curve, and where the needle points directly to the iron when held closely to it, it indicates the point where the line enters or leaves the iron. By shaking the needle to cause it to oscillate, a rough approximation can be obtained of the intensity of the field or the number of lines of force at different places. Great care should be taken not to move the needle too fast, as the lines of force in some machines make such short curves that the needle is demagnetized and even reversed in polarity before it has time to turn on its pivot. It is necessary, on account of this possible reversal of the magnetism, to test frequently its polarity at one of the machine poles, otherwise very queer and conflicting curves may be obtained.

The polarity of a magnet being usually represented by the signs + and —, the former indicating the north or

north-seeking pole, and the latter the south or south seeking pole, the direction which the external lines of force are conventionally assumed to have, is from + to —, that is, as if they emanated from the north pole of a magnet. If the compass needle or magnetoscope has an arrow head on its north end, the direction of this arrow will always show the direction of the lines of force of the field which is being explored.

It will greatly facilitate the examination and plotting of these curves to remember that every line of force appears to make a closed curve which encircles the wire through which the exciting current flows. This will also enable one to interpolate the probable return paths of the lines in the iron where their presence cannot be ascertained by means of a needle otherwise than by their external manifestations. All lines which do not pass from the pole pieces to the armature core and are therefore not cut by the armature coils, are wasted and represent leakage.

In the accompanying diagrams the probable return paths of a few of the lines of fŏrce in the iron parts have been indicated, and it is believed they are correct. The drawings may not in all cases represent the exact proportions of the frame, as they are copied from mere rough note-book sketches.

The first machine examined was the large Edison "Jumbo." Figure 1 shows the results obtained, copied from the rough sketches. As is well known, the frame of this machine is unsymmetrical, consisting of two horizontal sets of cylindrical, parallel magnets in the upper part, and one set in the lower. Each set consisting of four magnets, there were altogether eight magnets in the upper part and four in the lower. From this unequal distribution alone, it might have been supposed that either there would be considerable leakage of the excess of magnetism of the upper sets of magnets, the lower ones presenting only half the cross-section of iron, or that if the upper ones were only half saturated in order not to over-saturate the lower,

there were more magnets in the upper part than required to produce the needed magnetism. The coil of each lower magnet was found to be connected in series with the two

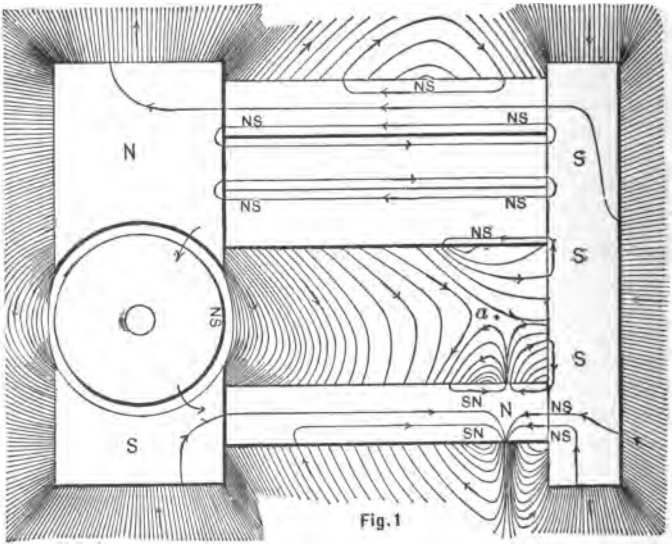


Fig. 1

above it, thus forming a series of three coils; these series groups were then connected in multiple arc with one another, forming a series-multiple group of three in series and four in multiple. If, therefore, the number of turns of wire was the same in each of the upper and lower coils, the upper half of the machine must have received twice the amount of magnetism that the lower had. From the external lines of force this appears in a measure to have been the case. The exploration of this field showed a somewhat peculiar distribution of magnetism which it was at first thought might be due partly to reversals of polarity of the exploring needle, but repeated examinations during which the needle was frequently tested for

polarity, showed that the results were quite correct, as might have been shown *á priori*, had it been known that the total ampere-turns in the upper part were much greater than those in the lower.

Beginning first with the upper pole-piece marked N, the usual intense leakage was observed on the surfaces and at the corners, and especially at the pole-piece projections, magnetically shunting the armature. Passing next along the upper magnet the first neutral point marked N S was found beyond the middle, the lines of force on the other side of it, entering instead of emanating from the cores, as before. Passing next to the upper end of the yoke-piece a strong south pole was found. The lower one of the upper magnets was found to be similar on its lower side, to the upper side of the upper magnet, only that the neutral point was nearer the yoke-piece than before,—neutral point being understood to mean a point where the two poles are exactly equal in intensity and where, therefore, the external lines of force are parallel to the cores. In a normal, straight bar magnet, the neutral point will always be in the middle, and might be termed the magnetic middle of a magnet, which in a normally proportioned bar magnet should coincide with its linear, axial middle.

In the space between these two upper parallel magnets, it was found that the lines of force were quite straight along their whole length, and parallel to the magnets, but in the opposite direction to their course in the cores. In other words, these two like magnets were neutral along their whole length on the sides facing each other. This might be considered as another proof that in two such parallel like coils ending in the same pole-piece, those parts of the coils which are nearest each other neutralize one another as far as the useful magnetism of the pole-piece is concerned ; it will be noticed that these parallel lines of force when continued, as shown, through the cores, encircle those portions of the coils.

Passing next down the yoke-piece it was found that instead of being neutral in the middle, as usual, with poles

at each end, it was a strong south pole along its whole length with no signs of a neutral point at any place. This is no doubt accounted for by the great excess of magnetism of the upper magnets over that in the lower.

The south or lower pole-piece was quite similar to the north, showing the usual intense leakage on all sides and corners and especially at the pole-piece projections.

Passing finally to the lowest magnet a very peculiar result was obtained, which was at first discredited, but upon repeated and careful exploring it was found to be verified. A short distance from the right hand end there was a very intense north pole, the lines of force being at that point quite perpendicular to the coil for a short distance, as shown, and afterwards branching out to the right and left, finally entering the iron again. Between this point and the yoke-piece, there was, of course, a neutral point, marked N S, and on the left hand side, also quite near to it, another neutral point of opposite polarity, marked S N. These two neutral points situated so very near a strong pole, created a very curious field, the most interesting part of which is that lying above them where the lines come together with those of the magnet above it. At this point, *a*, marked by a dot, it will be noticed that the lines which come together make four sharp turns as though there was something at this point which did not permit the lines to pass through but which reflected them somewhat as rays of light are reflected from a mirror. A needle held at this point acts as though it were uncertain in which direction to point, and if moved about this point even for very short distances, it will have very decided but quite different directions, as will be seen from the arrows which show the direction of the needle when in the respective lines of force. If a very short needle could be placed exactly at this point it would act similarly to a body balanced in unstable equilibrium, the slightest movement from this position causing the needle to deflect in a certain definite direction. Such points might therefore be termed "points of unstable magnetism," or "points of magnetic deflection

having four poles," as there are four general directions of the lines of force in the vicinity of this point. Their characteristic peculiarity is that the needle is very apt to have its polarity reversed when moved through them, the explanation of which is, no doubt, that the lines of force make such abrupt curves that their direction through the needle is reversed before it has time to turn on its pivot.

In a few places the probable courses of the lines of force through the iron itself, have been indicated. It is not possible to determine this definitely with the aid of a needle only, but from the nature of the field surrounding the iron and from the general laws of lines of force, it is very likely that the courses indicated are correct.

From the results obtained in the exploration of the field of this dynamo, the following conclusions may be drawn: Two similar parallel magnets, like those in the upper part, ending in the same pole and yoke-piece, are not to be recommended as there is considerable leakage between them. When the general form of the magnets for a dynamo is that of a simple **U** magnet, it should if possible be symmetrical magnetically as in an ordinary horse-shoe magnet. The magnetism of that part of the lower magnet between the letter N and the yoke-piece, is in the opposite direction to that generated by the ampere-turns on this part, from which it appears that the magnetism from a certain number of ampere-turns on other parts of the magnet is consumed in first neutralizing that in this part and then reversing it; it appears from the strong north pole on the lower magnet that the economy in the magnetism from the ampere-turns is poor, the reason being apparently in the unsymmetrical distribution of the iron and coils. As most of the lines of force shown in the figure do not pass through the armature, they represent leakage or wasted magnetism.

Figure 2 shows one-half of a normally proportioned Weston machine, the general type of frame being used also by numerous other makers. The field surrounding this

frame appears to be quite symmetrical above and below, which in fact would naturally follow from the symmetri-

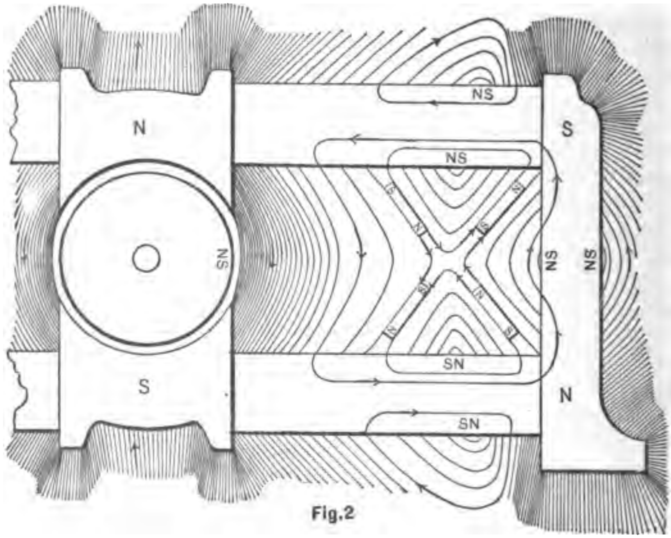


Fig.2

cal distribution of the iron and the magnetizing coils. The two neutral points on the upper and lower surfaces of the same magnet were not directly above each other, that on the outside surface being nearer the yoke-piece. Both the upper and lower coils showed strong poles at each end. The yoke-piece has strong poles at its ends and neutral points in the middle. No portions of the coils have reversed magnetism in them, which is no doubt due to the symmetrical distribution of the magnetism. A point of "unstable magnetism" or of "magnetic deflection" was found in this machine also, differing from the one observed in the Edison machine in the fact that the lines of force around it were symmetrically distributed. The gene-

ral character of the field at such a point is more clearly shown in this machine. The upper and lower lines of force having opposite directions or opposite polarity, will, according to the laws of lines of force, attract each other, forming sharp curves at their nearest point; the same is true of the lines on the right and left hand sides of this point, thus forming the four curves shown. The field at this point is similar to that produced by four bar magnets placed in the position shown, the opposite ones having like poles toward each other. It will be noticed that this point is bounded by four neutral points (one of which is in the armature) alternating with four poles, the successive neutral points and poles being alternately of opposite polarity, a neutral point being considered to be a point in the magnetic circuit around which the external lines of force are parallel to the axis, as described before. This is also true of that point in the Edison machine, only that the distribution is not as regular as in the Weston. In both these machines, and probably in all others having such **U** magnets with two coils, the complete iron circuit of the useful lines of force, beginning at one pole-piece thence successively through one magnet, the yoke-piece, the other magnet, the other pole-piece, and finally returning through the armature, includes four alternately opposite poles, separated by four neutral points of alternately opposite polarity, the polarity of the neutral points being indicated by N S or S N respectively. If the entire **U** magnet were made in the form of a circle wound over its whole length with coils, like a Faraday induction coil, and cut at one point for inserting the armature as in the Sir Wm. Thomson and the Mather machines, it is possible that this succession of poles and, therefore, also the point of magnetic deflection, would disappear.

Figure 3 shows a Sprague motor in which two neutral points were found near the far ends of two alternate coils, while none appeared to exist on the other coils. Unfavorable circumstances prevented the further examination of

this machine, but it is quite probable that it would prove to be similar to the Edison machine in figure 1, as there appeared to be two series-wound coils on two alternate magnets, and two shunt coils on the other two, which, unless

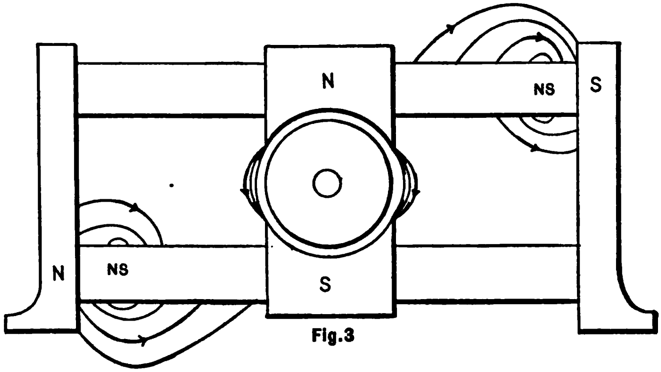


Fig.3

the ampere-turns were equal in both, would cause unequal distribution of magnetism; the location of the two neutral points, as shown, indicates that this may have been the case with this particular machine while it was being examined. The unsymmetrical distribution is probably intentional in this machine, to accomplish certain results.

Figure 4 shows the results obtained from a Van Depoele machine, the frame of which is of an entirely different class from those already shown. Only one-half is shown here; the coils surround the large massive cores which terminate each in one pole-piece. On the upper and lower side of the frame are two flat pieces which were presumably intended for yoke pieces to magnetically connect the south pole at the right hand end of the one core with the north pole at the other end of the other core. The exploration of the field, however, indicates that it performs the entirely different and very objectionable function of magnetically shunting the armature by inducing the other-

wise useful lines of force to leave the edge of the north pole-piece and return through this intended yoke-piece to the south or right hand end of the magnet, thus acting as a superfluous and objectionable yoke-piece to the two ends of the same magnet; the lines of force which should pass through the armature are therefore shunted off to one side. Furthermore, that portion of this flat piece which lies directly above the two pole-piece projections marked S and N, appears to short circuit, magnetically, these two pole pieces, or in other words, it magnetically shunts the armature, as a portion of the lines of force which should pass through the armature are led off around it and are, therefore, wasted. If this is as it appears to be, it might be better to omit these pieces altogether or to make them of some diamagnetic material.

The strongest leakage appears at the two pole-piece projections, the leakage being into the intended yoke-piece. This leakage extends along the side of the coil, nearly to the neutral point N S, which is near the farther end. The yoke-piece also exhibits a neutral point nearly above the one in the magnet and of the same polarity. As might be supposed, there is very intense leakage from the ends of the machine, the right hand end in the figure being a very strong south pole. But the leakage at this place does not necessarily represent wasted magnetism, as most of the lines of force which escape here no doubt pass through the armature after passing through the core of the magnet, and are therefore not wasted; their return course, however, is to a great extent through the air, thus making open circuit magnets as distinguished from closed circuit or iron-clad magnets in which the lines pass through iron along their whole course, and as the magnetic resistance of air is much greater than that of iron (according to Kapp 720 times that of iron) the magnetism must be weakened considerably in passing through so much air in its return circuit.

A peculiar field was noticed outside of the yoke-piece

almost directly above the middle of the machine. In moving the exploring needle horizontally at this place it suddenly made an abrupt turn of about 90° and over, indicat-

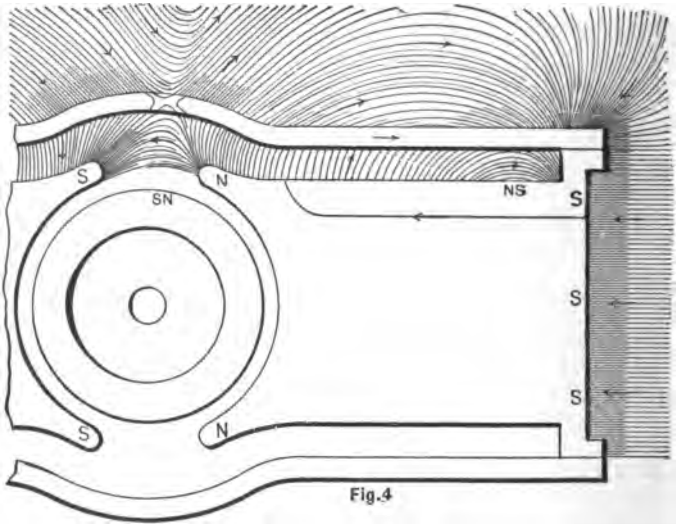


Fig. 4

ing a sharp turn of the lines of force at this point. Further examinations indicated that the lines of force had the direction as shown at this point, which can readily be explained on the assumption that there exists in the iron of the yoke-piece directly below these sharp curves, a point of deflection of magnetism or point of unstable magnetism as it was termed above, which has been indicated in the figure by four short curves. Not only do the lines of force all around this point indicate its presence, but in a very similar machine (figure 7) the same point was shown to exist in nearly the same relative position, being in this case in the air instead of in the iron, and its existence could therefore be determined definitely. If lines of force

form closed circuits in themselves it is probable that those which are deflected downward to this point without entering the iron, are the return circuits of those which leak out at the two ends of the machine.

The field around the Thomson-Houston machine, shown in figures 5, 6 and 7, proved to be one of the most interesting, some of the curves being of a very peculiar nature. The magnetism was so intense in several places and the lines made such sharp turns that the exploring needle was repeatedly reversed in polarity during the examination, thus giving absurd results. It was not until the needle was repeatedly tested for polarity, and all results obtained with a reversed needle discarded, that any conclusive results could be obtained. The test was furthermore rendered difficult at first by the fact that the direction of the lines of force could not be tested in one plane only as in the other machines, as they curved around in different planes in such a way as to make it difficult to represent their courses on the plane of the drawing. In order to be sure that the results were correct the writer recently repeated the tests very carefully on a new 30-light arc machine, and obtained the results shown in the figures, which are believed to be substantially correct.

Figure 5 shows more than half of the vertical cross-section through the centre, taken perpendicularly to the shaft. The coils are wound around the large, hollow cast-iron cores which terminate at the armature and at the ends of the machine, one of which is shown complete. There is a round opening in the thin shell which embraces the right and left hand sides of the armature. The intended yoke-piece consists of a series of horizontal, round, wrought-iron bars, two of which are shown, one above and the other below the armature. It is, therefore, similar in general outline to the Van Depoele machine in figure 4, and the results should therefore agree to a certain extent with those shown in figure 4, which was found to be the case. As in the Van Depoele, there was a very strong leakage from the magnets

to the yoke-piece, especially at and near the ends of the pole pieces, showing that many lines of force were magnetically shunted around the armature, and were therefore wasted. A neutral point was found near the right hand

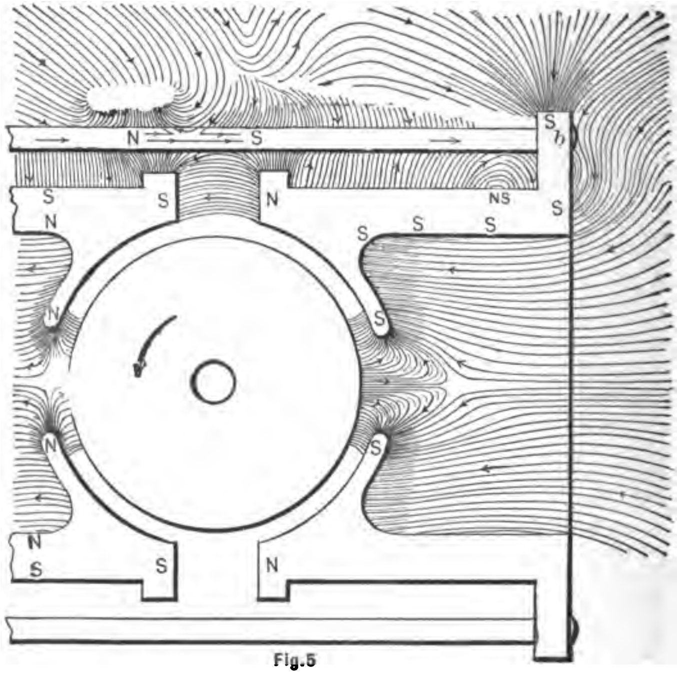


Fig. 5

end of the core as shown. Immediately above the bars of the yoke-piece a strong field existed which showed the same polarity as that between the yoke and pole-piece, as indicated by the arrows, showing that these yoke-pieces had two strong poles one above each of the pole pieces, but of opposite polarity to the latter. Immediately above this

field and represented by an open space, the needle exhibited that peculiar state of unstability, indicating a point of deflection, while above this space it again had a definite and decided direction. In this space, left blank on the figure, the lines were found to be perpendicular to the plane of the drawing, as is shown more clearly in figure 6, which is

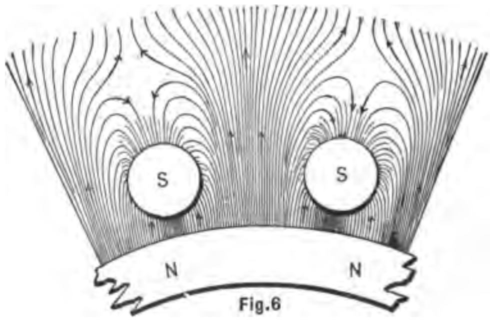


Fig.6

an enlarged vertical cross-section taken through the north pole-piece perpendicular to the bars of the yoke-piece. As shown in this figure the lines passed from the pole-piece into the yoke-piece on all sides, while the others from the pole-piece pass out into the air between the bars, thus forming above the bars at about the relative distance shown, a point of deflection having four poles, similar to that in the Edison and Weston machines.

Referring again to figure 5 a peculiar deflection of the lines was noticed almost directly above the south pole-piece, which was somewhat similar to that observed in the Van Depoele machine. It is possible that this was due to another point of deflection existing in the iron, as indicated in figure 5, with four or possibly six poles, but these curves in the iron itself are probable conjectures only. A similar deflection was noticed a few inches to the left of this point.

In moving the exploring needle vertically above the

north pole-piece, it was found to turn abruptly through almost 180° a few inches above the yoke-piece, as shown by the arrows, while nearly above this there was a deflection similar to that in figure 4. This was found to be due to a point of deflection existing between the bars but above them, and is shown more clearly in figure 7, which

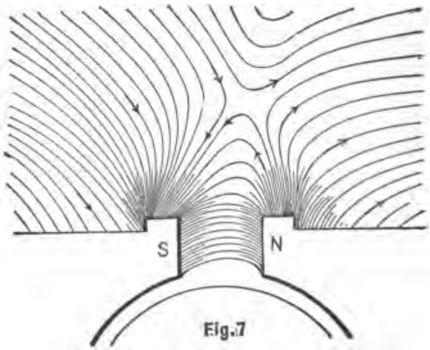


Fig. 7

represents a portion of a section like figure 5, but between the bars. This point was clearly indicated by the needle, and assists in connection with figures 5 and 6, in explaining some of the peculiar curves noticed above that part of the yoke-piece which lies above the pole pieces in figure 5.

At the right hand end of the core the usual strong pole was found. A peculiar curving of the lines was noticed at *b*, where the rounded projections of the wrought-iron bars passed through the flanges. A possible explanation of this is, that the cast-iron flange is over-saturated to a greater extent than this projection of the wrought-iron bar, which, therefore, attracts the lines.

Following the surface of the core to the inside or hollow portion, a weak south pole was found to exist on the cylindrical surface, while on the interior flange embracing the armature, the south pole was found to be very strong, the lines from it passing out through the open end. By placing

a small needle very near the revolving armature and in the opening in the iron, it was found that many of the lines from this south pole entered the armature. From the general principles underlying all other dynamos, it would be supposed that the polarity of the pole-piece embracing the right hand half of the armature, was the same in all parts, but it appears from the external lines of force which could be examined, that this is not the case with this machine as there is a strong north and a strong south pole on different parts of the same pole-piece. Careful and repeated examinations with the exploring needle on the same and on different machines clearly shows this peculiar disposition of poles to exist.

Near the opening through the centre of the core, was another point of deflection with four poles, which in some machines was found to be very near the armature, as shown on the left hand side, while in others it was located several inches from the armature as shown on the right hand side. The lines of force at this point were very intense, and their curved directions were very decided, for this reason it was found that a very short needle had to be used and that it had to be moved about very slowly to prevent it from having its polarity reversed before it could respond to the change of direction. By moving the needle rapidly from the armature through this point of deflection, its polarity can readily be reversed, and it will then point in the same direction as it did before passing the point, thus making it appear as if there was no point of deflection. Moving the needle toward the armature will not reverse it so readily as these curves are less abrupt.

The lines of force at this point appear to oscillate very rapidly, which is probably due to the pulsating character of the magnetizing current. If, therefore, a small induction coil in the form of a simple coil of copper wire, be held concentric with this opening in the core and near to it, an alternating current would no doubt be induced in it. A

telephone in series with this coil will indicate the presence of such alternating currents by a buzzing sound, the note emitted being apparently dependent on the speed and number of coils of the armature.

It is quite probable that the curves shown in all these figures would change very much with different degrees of saturation. A careful study of the curves of each machine at regularly increasing degrees of saturation, might lead to a determination of the best proportions and shapes of the iron parts.

Figures 4 and 5 are good illustrations of how not to proportion the parts when the best economy of magnetization is desired. At the same time it must not be forgotten that the energy used to excite the magnetism is for the best machines only a few per cent. of the whole output, and that, therefore, any improvements in the frame that would economize magnetism would only lessen this already small fraction, and possibly in some cases economize material. Other conditions may be of so much more importance as to make an increase in the economy of magnetism of little significance in comparison. The fact that the Thomson-Houston machines are used in such large numbers, shows that great economy of magnetism is not one of the most important points about a machine.

It is often represented as a good feature of a machine that its magnets are very powerful and will hold very heavy weights ; a little consideration, however, will show that such external magnetism, especially when at the pole pieces, represents leakage and waste, and, therefore, is an objectionable feature. It would be much more creditable to a designer of a machine to be able to show that when running with its full load the magnets will not even attract a small bunch of keys, all the magnetism being diverted into the armature where it is wanted.

From the nature of the fields surrounding a dynamo, as shown in the figures, the following general deductions may be made. That machines exhibit the following mag-

netic properties : Free north and south poles, neutral points of two different polarities, and points of deflection ; the latter exist in the external fields but may possibly exist also in the iron itself ; they generally appear as four curvatures of the lines of force towards and receding from one point, and are in that case enclosed by four free poles and four neutral points of alternately opposite polarity. That the lines of force in and around a magnet appear to have the following properties : Like lines repel, unlike lines attract each other ; they never intersect ; they appear to form circuits or paths closed in themselves and surrounding the current generating them ; when not prevented by other forces they take the shortest distance between the iron parts. The illustrations of these statements in the special cases shown, is not offered as a proof of their correctness in all cases, they are given here only as general guides in exploring and plotting such fields.

APPENDIX IV.

*Systems of Cylinder-Armature Windings.**

THE cylindrical surface of the armature is for convenience in winding divided into sections or fields. In the accompanying illustrations the number of sections (denoted by heavy lines) has been made equal to the number of coils, in which case each coil must fill one half of each of two opposite sections.

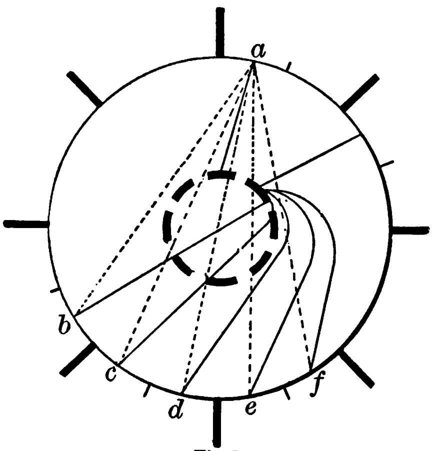


Fig. 1.

In figure 1, starting at the upper commutator bar, the wire is wound into the first half of the first section, thence back through one of the opposite half sections *b*, *c*, *d*, *e*, or *f*, and thence to the next commutator bar, completing one coil. By winding into the diametrically opposite half sections *a* and *d*, it will be the Siemens winding, shown completed in figure 2. By winding into *a* and *e* it will be the Froehlich winding, figure 3; *a* and *c* will be the Breguet winding; *a* and *b*, or *a* and *f* will both give such irregular windings that they should not be used. The accompanying diagrams show the completed windings, and the five principal modifications of the same.

* Abstract from an article on Cylinder-Armatures in the *Electrician and Electrical Engineer*, Vol. 4, 1885, p. 423, and Vol. 5, 1886, p. 84.

In these figures the windings are shown diagrammatically as seen from the commutator end of the armature, the dotted lines representing the winding across the other (pulley) end of the armature. The two halves of the armature being in multiple arc, those sets of coils which form one half are shown by white coil spaces, and will be termed light coils, while those forming the other half are shown by section lined coil spaces, and will be termed dark coils. The coil spaces which are marked with crossed lines represent the coils which are short-circuited by the brushes. The arrow heads on the lines show the direction in which the current will flow in those wires when the armature revolves to the left, as shown by the arrow on the outside, and when the polarity and the position of the pole-pieces is as shown by the letters *N* and *S*. The commutator connections of the dead coils which are short-circuited by the brushes are indicated by the letters *O O* and have no arrow heads. To avoid too many lines the brushes are drawn outside of the armature, their proper place on the commutator being shown by a small dot. The diagrams thus show at a glance whether the winding is symmetrical, whether the light and dark coils of the two halves of the armature are symmetrically situated in the fields, in what part of the field the dead coils lie, the position and polarity of the brushes, etc.

The windings have all been started alike by connecting the beginning of the first coil to the nearest commutator bar, this being the usual way. They may, however, be started from any other commutator bar, without changing the system of winding, by merely shifting the brush line or the relative position of the commutator bars (and brushes) with their respective coils.

The Siemens or Hefner-Alteneck winding, figure 2, is irregular after one half of the armature is wound (between the two lower white sections). The coils have not symmetrical positions in the fields. At least one of the short-circuited coils, being in opposite fields, is not dead. All the coils cross each other on the ends of the armature, making a bulky "head." It appears to be no longer used, presumably owing to these objections.

The Froehlich winding, figure 3, is quite regular. The dark and light coils have symmetrical positions in the fields. Each

short-circuited coil lies in one field and is therefore more nearly dead; the injurious currents in them will therefore be less than in the Siemens. Every two coils being parallel there will be much fewer crossings of wires at the ends, which is an additional advantage. In this system special care should be taken that the coils are wound in their proper spaces, as there are always two, for instance *i* and *h*, which are opposite to one, *g*, *i* is the right one and *h* the wrong one.

The Breguet winding, figure 4, is practically identical with the Froehlich; the only difference is in the relative positions of the commutator bars (brush line) and their respective coils.

The Edison system, figure 5, is the Siemens applied to an odd number of coils. It is quite regular and the light and dark coils are symmetrically situated. Only one coil is short-circuited, instead of two, as in the other systems. All the coils cross each other as in the Siemens. It is simpler to wind than either of the others. Using an odd number of coils, and winding from *a* to *c*, figure 5, instead of *a* to *b*, will give a very irregular winding, while from *a* to *d* will give a regular one.

Instead of winding two neighboring coils next to one another, as in figures 2 and 3, they may be wound over each other, thus giving the double Siemens and double Froehlich windings shown in figures 6 and 7. The advantage is that they are easier to wind. They have the same characteristics as in the first forms, with the additional disadvantage that the outer and inner coils have different mean lengths and speeds. The Edison system may also be wound double, but it then appears to lose its characteristic regularity.

In the Weston winding, figure 8, and the Hering winding, figure 9, each coil is split into two halves, one half being wound in the lower layers and one half in the upper layers. This makes the mean length and speed of the coils the same, and therefore overcomes the objection to the double windings. They are somewhat more troublesome to wind. The Weston is based on the Siemens, and has all the characteristics of that system, the objectionable effect of the irregularity being, however, greatly reduced. The Hering winding is based on the Froehlich, and has all the characteristics of that system.

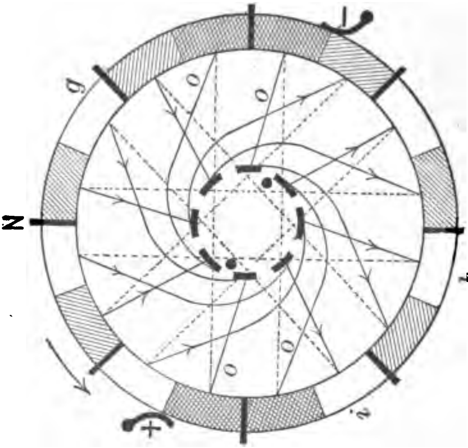


Fig. 3.
FROEHLICH.

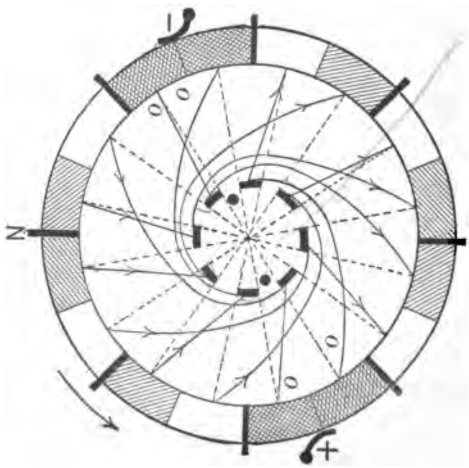


Fig. 2.
SIEMENS. (HEFNER-ALTENECK).

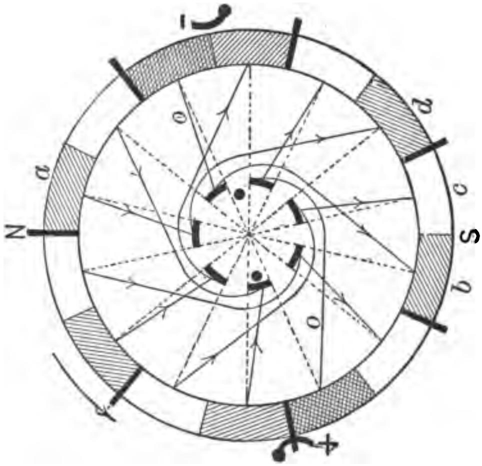


Fig. 5.
EDISON.

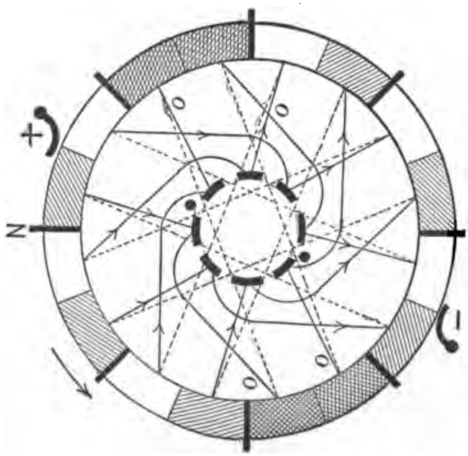


Fig. 4.
BREGUET.

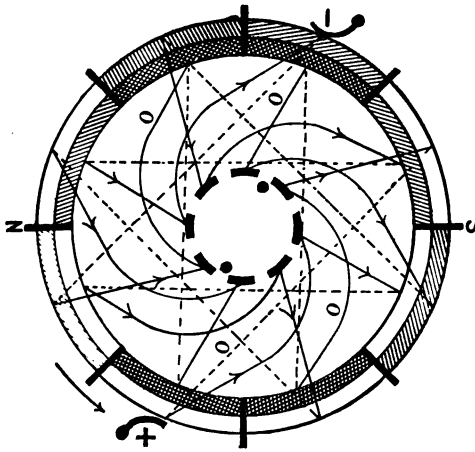


Fig. 7.
Double wound Froehlich.

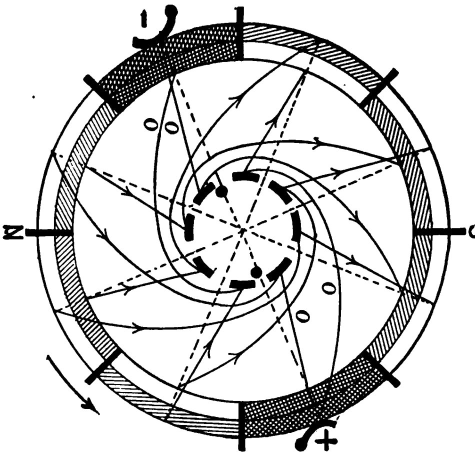


Fig. 6.
Double wound Siemens.

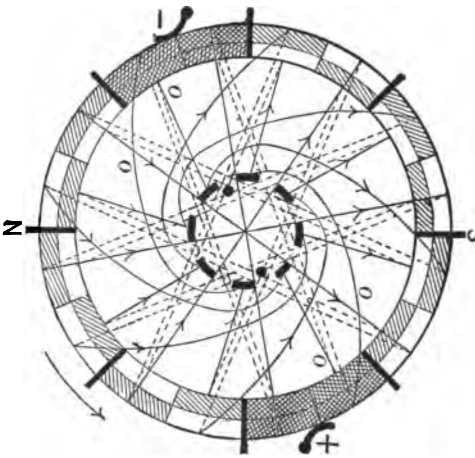


Fig. 9.
HERING.
(SPLIT COIL DOUBLE WOUND FROEHLICH).

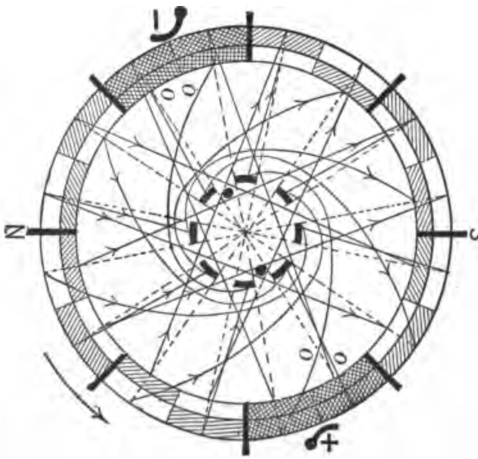


Fig. 8.
WESTON.
(SPLIT COIL DOUBLE WOUND SIEMENS).

APPENDIX V.

Equivalents of Units of Measurement.

THE numbers in these tables have all been calculated from the following set of fundamental standard equivalents, viz.:

The values of—

the meter in inches,
the gram in grains,
the avoirdupois pound in grains,
the troy (apothecary) pound in grains,
the gallon in cubic inches,
the atmospheric pressure in millimeters of mercury,
the specific gravity of mercury,
Joules equivalent 772,
acceleration of gravity 981,
legal ohm in mercury units,
B. A. unit of resistance in legal ohms.

The numerical values which were used for this set of fundamental equivalents are those given in their respective places in the tables. For any subsequent, more accurate, determination of these fundamental values the corresponding corrections of their derived equivalents in these tables can readily be made by simple proportion. For this reason the derived equivalents have in many cases been carried to more decimals than would otherwise be reasonable. The values for the weights and volumes of water are based on the metric system.

In almost all cases the reciprocal of each equivalent is also given (in its proper place), thus enabling all calculations to be made by multiplication instead of division.

The "Approximate Values" have been given in the smallest number of digits, generally only one or two besides the digits 0 and 1. Almost all of these approximate values are within 3% of the correct value, and many of them within 2%.

All the equivalents have been calculated by two independent methods, and it is believed that there are no errors.

EQUIVALENTS OF UNITS OF MEASUREMENT.

CARL HERING.

UNITS. (In order of size.)	EQUIVALENTS.		APPROXIMATE VALUES, WITHIN A FEW PER CENT.	LOGARITHMS.
Lengths.				
1 mil	= .025400	millimeters	$\frac{1}{40}$	$\bar{2}$.404 8259
"	= .001	inch	$\frac{1}{1000}$	$\bar{3}$.000 0000
1 millimeter	= 39.3708	mils	40	1.595 1741
"	= .039371	inch	$\frac{1}{25}$	$\bar{2}$.595 1741
1 centimeter	= .393708	inch	$\frac{4}{10}$	$\bar{1}$.595 1741
1 inch	= 2.53995	centimeters	$\frac{10}{4}$	0.404 8259
1 foot	= .30479	meter	$\frac{3}{10}$	$\bar{1}$.484 0071
1 yard	= .91438	meter	$\frac{10}{11}$	$\bar{1}$.961 1284
1 meter	= 39.370790	inches	40	1.595 1741
"	= 3.280899	feet	$\frac{10}{3}$	0.515 9929
"	= 1.09363	yards	$\frac{11}{10}$	0 038 8716
1 kilometer	= 3280.899	feet		3.515 9929
"	= 1093.633	yards		3.038 8716
"	= .62138	mile	$\frac{5}{8}$	$\bar{1}$.793 3590
1 mile	= 5280.	feet		3.722 6339
"	= 1760.	yards		3.245 5126
"	= 1609.31	meters		3.206 6410
"	= 1.60931	kilometers	$\frac{8}{5}$	0.206 6410
"	= .86838	geog. or naut. mile	$\frac{7}{8}$	$\bar{1}$.938 7098
1 geog. or naut. mile	= 6080.27	feet		3.783 9229
Surfaces.				
1 sq. mil	= .00064514	sq. millimeters		$\bar{4}$.809 6518
"	= .000001	sq. inch		$\bar{6}$.000 0000
1 sq. millimeter	= 1550.1	sq. mils		3.190 3482
"	= .001550	sq. inch		$\bar{3}$.190 3482
1 sq. centimeter	= .15501	sq. inch	$\frac{2}{13}$	$\bar{1}$.190 8482
1 sq. inch.	= 6.4514	sq. centimeters	$\frac{13}{2}$	0.809 6518
1 sq. decimeter	= 15.501	sq. inches	$\frac{31}{2}$	1.190 3482
"	= .10764	sq. foot	$\frac{3}{28}$	$\bar{1}$.031 9858
1 sq. foot	= 929.00	sq. centimeters		2.968 0142
"	= 9.2900	sq. decimeters	$\frac{65}{7}$	0.968 0142
1 sq. yard	= .83610	sq. meter	$\frac{10}{12}$	$\bar{1}$.922 2568
1 sq. meter	= 10.764	sq. feet	$\frac{43}{4}$	1.031 9858
"	= 1.1960	sq. yards	$\frac{12}{10}$	0.077 7432
1 are	= 100.	sq. meters		2.000 0000
1 acre	= .40467	hectare	$\frac{4}{10}$	$\bar{1}$.607 1020
"	= .0040467	sq. kilometer		$\bar{3}$.607 1020
1 hectare	= 10000.	sq. meters		4.000 0000
"	= 2.4711	acres	$\frac{5}{2}$	0.392 8980
1 sq. kilometer	= 247.11	acres		2.392 8980
"	= .38612	sq. mile	$\frac{10}{26}$	$\bar{1}$.586 7180
1 sq. mile	= 640.	acres		2.806 1800
"	= 2.5899	sq. kilometers	$\frac{26}{10}$	0.413 2820

Volumes.

1 cub. centimeter	= .061027	cub. inch	$\frac{2}{33}$	$\bar{2}$.785 5223
"	= .033816	fluid ounce	$\frac{1}{30}$	$\bar{2}$.529 1203
"	= .0021135	pint		$\bar{3}$.325 0003
1 fluid drachm	= 3.6965	cub. centimeters	$\frac{11}{3}$	0.567 7897
"	= .22559	cub. inch	$\frac{2}{9}$	$\bar{1}$.353 3120
1 cub. inch	= 16.386	cub. centimeters	$\frac{33}{2}$	1.214 4777
"	= .55411	fluid ounce	$\frac{5}{9}$	$\bar{1}$.743 5980
"	= .034632	pint	$\frac{7}{200}$	$\bar{2}$.539 4780
"	= .016386	liter	$\frac{1}{60}$	$\bar{2}$.214 4777
1 fluid ounce	= 29.572	cub. centimeters	30	1.470 8797
"	= 8.	fluid drachms		0.903 0900
"	= 1.8047	cub. inches	$\frac{9}{5}$	0.256 4020
1 pint	= 473.15	cub. centimeters		2.674 9997
"	= 28.875	cub. inches	$\frac{202}{7}$	1.460 5220
"	= 16.	fluid ounces		1.204 1200
"	= .47315	liter	$\frac{10}{21}$	$\bar{1}$.674 9997
1 quart	= 946.30	cub. centimeters		2.976 0297
"	= 57.7500	cub. inches		1.761 5520
"	= .94630	liter	$\frac{20}{21}$	$\bar{1}$.976 0297
"	= .033420	cub. foot	$\frac{1}{30}$	$\bar{2}$.524 0084
1 liter	= 1000.	cub. centimeters		3.000 0000
"	= 61.027	cub. inches		1.785 5223
"	= 2.1135	pints	$\frac{21}{10}$	0.325 0003
"	= 1.0567	quarts	$\frac{21}{20}$	0.023 9703
"	= .26419	gallon	$\frac{8}{30}$	$\bar{1}$.421 9103
"	= .035317	cub. foot	$\frac{6}{170}$	$\bar{2}$.547 9787
1 gallon	= 3785.2	cub. centimeters		3.578 0897
"	= 231.0000	cub. inches	$\frac{700}{3}$	2.363 6120
"	= 3.7852	liters	$\frac{30}{8}$	0.578 0897
"	= .13368	cub. foot	$\frac{2}{15}$	$\bar{1}$.126 0683
"	= .037852	hectoliter	$\frac{3}{80}$	$\bar{2}$.578 0897
1 cub. foot	= 28315.3	cub. centimeters		4.452 0213
"	= 29.922	quarts	30.	1.475 9916
"	= 28.3153	liters	$\frac{170}{6}$	1.452 0213
"	= 7.4805	gallons	$\frac{15}{2}$	0.873 9317
"	= .28315	hectoliter	$\frac{2}{7}$	$\bar{1}$.452 0218
"	= .028315	cub. meter	$\frac{2}{70}$	$\bar{2}$.452 0213
1 hectoliter	= 105.67	quarts		2.023 9703
"	= 100.	liters		2.000 0000
"	= 26.419	gallons	$\frac{80}{3}$	1.421 9103
"	= 3.5317	cub. feet	$\frac{7}{2}$	0.547 9787
1 cub. yard	= 201.97	gallons		2.305 2955
"	= .76451	cub. meter.	$\frac{10}{13}$	$\bar{1}$.883 8852
1 cub. meter	= 264.19	gallons		2.421 9103
"	= 35.317	cub. feet	$\frac{70}{2}$	1.547 9787
"	= 1.3080	cub. yards	$\frac{13}{10}$	0.116 6148
1 stere	= 1.	cub. meter		0.000 0000

Weight.

1 milligram	= .015432	grain	2/130	$\bar{2}$.188 4320
1 grain	= 64.799	milligrams		1.811 5680
1 gram	= 15.43235	grains	15.	1.188 4320
"	= .035274	ounce avdp.	7/200	$\bar{2}$.547 4539
"	= .032151	ounce troy	8/250	$\bar{2}$.507 1908
1 ounce avdp.	= 437.50	grains		2.640 9781
"	= 28.3495	grams	200/7	1.452 5461
"	= .91146	ounce troy	10/11	$\bar{1}$.959 7369
1 ounce troy	= 480.	grains		2.681 2412
"	= 31.1035	grams	31.	1.492 8092
"	= 1.0971	ounces avdp.	11/10	0.040 2631
1 pound troy	= 5760.	grains		3.760 4225
"	= 12.	ounces troy		1.079 1812
"	= .82286	pound avdp.	5/6	$\bar{1}$.915 3245
"	= .37324	kilogram	3/8	$\bar{1}$.571 9905
1 pound avdp.	= 7000.	grains		3.845 0980
"	= 16.	ounces avdp.		1.204 1200
"	= 1.2153	pounds troy	6/5	0.084 6755
"	= .45359	kilogram	10/22	$\bar{1}$.656 6660
1 kilogram	= 35.274	ounces avdp.	70/2	1.547 4539
"	= 2.2046	pounds avdp.	22/10	0.343 3340
1 net or short ton	= 2000.	pounds avdp.		3.301 0300
"	= .90719	metric ton	10/11	$\bar{1}$.957 6960
"	= .89286	long ton	9/10	$\bar{1}$.950 7820
1 metric ton	= 2204.62	pounds avdp.		3.343 3340
"	= 1.1023	short tons	11/10	0.042 3040
"	= .98421	long ton	60/61	$\bar{1}$.993 0860
1 gross or long ton	= 2240.	pounds avdp.		3.350 2480
"	= 1.1200	short tons	10/9	0.049 2180
"	= 1.01605	metric tons	61/60	0.006 9140

Weights and Lengths.

1 lb. per mile	= .28185	klgr. per kilometer	2/7	$\bar{1}$.450 0250
"	= .11048	grain per inch	1/9	$\bar{1}$.043 2829
"	= .0028185	gram per centimeter	2/700	$\bar{3}$.450 0250
1 klgr. per kilomet.	= 3.5479	lbs. per mile	7/2	0.549 9750
"	= .39197	grain per inch	4/10	$\bar{1}$.593 2579
"	= .01000	gram per centimeter		$\bar{2}$.000 0000
1 grain per inch	= 9.0514	lbs. per mile	9.	0.956 7171
"	= 2.5512	klgs. per kilometer	10/4	0.406 7421
"	= .025512	gram per centimeter	1/40	$\bar{2}$.406 7421
"	= .0025512	klg. per meter	1/400	$\bar{3}$.406 7421
"	= .0017143	lb. per foot		$\bar{3}$.234 0832
1 gram per centimet.	= 354.79	lbs. per mile	700/2	2.549 9750
"	= 100.000	klgs. per kilometer		2.000 0000
"	= 39.197	grains per inch	40	1.593 2579
"	= .10000	klg. per meter		$\bar{1}$.000 0000
"	= .067196	lb. per foot	2/30	$\bar{2}$.827 3411
1 klg. per meter	= 391.97	grains per inch	400	2.593 2579
"	= 10.	grams per centimeter		1.000 0000
"	= .67196	lb. per foot	2/3	$\bar{1}$.827 3411
1 lb. per foot	= 583.33	grains per inch		2.765 9168
"	= 14.882	grams per centimeter	30/2	1.172 6589
"	= 1.4882	klgs. per meter	3/2	0.172 6589

Weights and Surfaces (Pressures).

1 lb. per sq. inch	= .068044	atmosphere	[illegible]	$\bar{2}$.832 7894
"	= .070310	klgr. per sq. centimeter	[illegible]	$\bar{2}$.847 0142
1 klgr. per sq. centim.	= 14.223	lbs. per sq. inch	[illegible]	1.152 9858
"	= .96778	atmosphere	[illegible]	$\bar{1}$.985 7752
1 atmosphere	= 760.	millimeters of mercury col.		2.880 8136
"	= 33.901	feet water column	34	1.530 2177
"	= 29.922	inches of mercury column	30.	1.475 9877
"	= 14.696	lbs. per sq. inch	[illegible]	1.167 2106
"	= 10.333	meters water column	[illegible]	1.014 2248
"	= 1.0333	klgs. per sq. centimeter	[illegible]	0.014 2248
sp. gr. of mercury	= 13.596		[illegible]	1.133 4112

Weights and Volumes.

1 grain per cub. inch	= .24686	lb. per cub. foot	1/4	$\bar{1}$.392 4457
"	= .0039545	gram per cub. centimeter	4/1000	$\bar{3}$.597 0903
1 lb. per cub. foot	= 4.0509	grains per cub. inch	4	0.607 5543
"	= .016019	gram per cub. centimeter	8/500	$\bar{2}$.204 6447
"	= .016019	kilgr. per liter	8/500	$\bar{2}$.204 6447
1 gram per cub. c. m.	= 252.88	grains per cub. inch.	1000/4	2.402 9097
1 gram per cub. c. m.	= 62.425	lbs. per cub. foot	500/8	1.795 3553
1 klgr. per liter	= 62.425	lbs. per cub. foot	500/8	1.795 3553
"	= 2.0862	lbs per quart	[illegible]	0.319 3637
1 lb. per quart	= .47933	klgr. per liter	[illegible]	$\bar{1}$.680 6363
1 lb. per cub. inch	= .027681	klgr. per cub. c. m.	[illegible]	$\bar{2}$.442 1888
1 klgr. per cub. c. m.	= 36.125	lbs. per cub. inch	36.	1.557 8117

Weight of Water. K.

1 cub. c. m. water weighs	15.432	grains	15.	1.188 4820
"	1.	gram	1	0.000 0000
1 cub. inch weighs	252.88	grains	1000/4	2.402 9097
"	16.386	grams	[illegible]	1.214 4777
"	.036125	pound	[illegible]	$\bar{2}$.557 8117
1 quart weighs	2.0862	pounds	[illegible]	0.319 3637
"	.94630	kilogram	[illegible]	$\bar{1}$.976 0297
1 litre weighs	2.2046	pounds	[illegible]	0.343 3340
1 cub. foot weighs	62.425	pounds	500/8	1.795 3553
"	28.3153	kilograms	[illegible]	1.452 0213
1 cub. yard weighs	1685.5	pounds		3.226 7192
"	764.51	kilograms		2.883 3852
1 cub. metre weighs	2204.6	pounds		3.343 3340

M.

1 pound water measures	453.59	cub. centimeters		2.656 6660
"	27.681	cub. inches	[illegible]	1.442 1888
"	.47933	quarts	[illegible]	$\bar{1}$.680 6363
"	.45359	liter	[illegible]	$\bar{1}$.656 6660
"	.016019	cub. foot	[illegible]	$\bar{2}$.204 6447
1 klgr. water measures	61.027	cub. inches		1.785 5223
"	1.0567	quarts	[illegible]	0.023 9703
"	1.	liter		0.000 0000
"	.035317	cub. foot	[illegible]	$\bar{2}$.547 9787

The weight of a given volume of any other material, whether solid or liquid, is its specific gravity multiplied by the factor *K*. The volume of a given weight of any other material, is the factor *M* divided by its specific gravity.

		Velocities.		
1 foot per second	= .30479	meter per second	$\frac{3}{10}$	$\bar{1}$.484 0071
"	= .018288	klmet. per minute	$\frac{2}{110}$	$\bar{2}$.262 1583
"	= .011364	mile per minute	$\frac{8}{700}$	$\bar{2}$.055 5173
1 meter per second	= 3.280899	feet per second	$\frac{10}{3}$	0.515 9929
"	= .0600	klmet. per minute	$\frac{6}{100}$	$\bar{2}$.778 1513
"	= .037283	mile per minute	$\frac{1}{27}$	$\bar{2}$.571 5102
1 kilometer per minute	= 54.682	feet per second	55.	1.737 8417
"	= 16.667	meters per second	$\frac{100}{6}$	1.221 8487
"	= .62138	mile per minute	$\frac{5}{8}$	$\bar{1}$.793 3590
1 mile per minute	= 88.00	feet per second		1.944 4827
"	= 26.822	meters per second	27	1.428 4898
"	= 1.60931	klmet. per minute	$\frac{8}{5}$	0.206 6410
		Gravity.		
Acceleration of gravity =	981.000	centimeters per second	1000.	2.991 6690
	32.186	feet per second	$\frac{100}{3}$	1.507 6619
		Forces (see also Weights).		
1 dyne	= 1.0194	milligrams	1.	0.008 3310
"	= .015731	grain	$\frac{4}{250}$	$\bar{2}$.196 7630
"	= .0010194	gram	$\frac{1}{1000}$	$\bar{3}$.008 3310
"	= .00003596	ounce avoirdupois		$\bar{5}$.555 7849
1 milligram	= .981	dyne	1.	$\bar{1}$.991 6690
1 grain	= 63.568	dynes	$\frac{500}{8}$	1.803 2370
1 gram	= 981.	"	1000	2.991 6690
1 ounce avdp.	= 27811.	"		4.444 2151
1 pound avdp.	= 444976.	"		5.648 3351
1 kilogram	= 981000.	"		5.991 6690
		Work.		
1 erg	= 1.	dyne-centimeter	1	0.000 0000
"	= .0000001	joule		$\bar{7}$.000 0000
1 gram-centimeter	= 981.00	ergs	1000	2.991 6690
"	= .00001	kilogram-meter		$\bar{5}$.000 0000
1 foot-grain	= 1937.5	ergs		3.287 2441
1 joule, or 1 volt-coulomb, or 1 watt during every second, or 1 volt-ampere during every second	= 10,000,000.	"		7.000 0000
	= .737324	foot-pound	$\frac{3}{4}$	$\bar{1}$.867 6580
	= .101937	kilogram-meter	$\frac{1}{10}$	$\bar{1}$.008 3310
	= .0013592	metric horse-power for one second	$\frac{4}{3000}$	$\bar{3}$.133 2698
	= .0013406	horse-power for one second	$\frac{4}{3000}$	$\bar{3}$.127 2954
"	= .0009551	pound-Fah., heat unit	$\frac{2}{2100}$	$\bar{4}$.980 0407
"	= .0005306	pound-Centig., heat unit	$\frac{6}{11000}$	$\bar{4}$.724 7682
"	= .0002407	kilogr.-Centig., "	$\frac{12}{50000}$	$\bar{4}$.381 4342
"	= .0002778	watt-hour	$\frac{3}{11000}$	$\bar{4}$.443 6975
1 foot-pound	= 13562600.	ergs		7.132 3420
"	= 1.35626	joules	$\frac{4}{3}$	0.132 3420
"	= .13825	kilogram-meter	$\frac{7}{50}$	$\bar{1}$.140 6730
"	= .0018434	metric horse-power for one second	$\frac{2}{1100}$	$\bar{3}$.265 6117
"	= .00181818	horse-power for one second	$\frac{2}{1100}$	$\bar{3}$.259 6373

Work.—(Continued.)

1 foot-pound	= .0012953	pound-Fah., heat unit	$\frac{4}{3000}$	$\bar{3}$.112 3827
"	= .0007196	pound-Centig., heat unit	$\frac{5}{7000}$	$\bar{4}$.857 1102
"	= .0003264	kilogr.-Centig., "	$\frac{1}{3000}$	$\bar{4}$.513 7762
"	= .0003767	watt-hour	$\frac{3}{8000}$	$\bar{4}$.576 0395
1 kilogram-meter	= 98100000.	ergs		7.991 6690
"	= 9.81000	joules	10.	0.991 6690
"	= 7.23314	foot-pounds	$\frac{50}{7}$	0.859 3270
"	= .01333	metric horse-power for one second	$\frac{4}{300}$	$\bar{2}$.124 9387
"	= .013151	horse-power for one second	$\frac{4}{300}$	$\bar{2}$.118 9643
"	= .009369	pound-Fah., heat unit	$\frac{3}{320}$	$\bar{3}$.971 7097
"	= .005205	pound-Centig., heat unit	$\frac{11}{2100}$	$\bar{3}$.716 4372
"	= .002361	kilogr.-Centig., "	$\frac{7}{3000}$	$\bar{3}$.373 1032
"	= .002725	watt-hour	$\frac{3}{1100}$	$\bar{3}$.435 3670
1 watt-hour	= 3600.	joules		3.556 3025
"	= 2654.4	foot-pounds	$\frac{8000}{3}$	3.423 9605
"	= 366.97	kilogram-meters	$\frac{1100}{3}$	2.564 6335
"	= 3.4383	pound-Fah., heat units	$\frac{10}{3}$	0.536 3433
"	= 1.9102	pound-Centig., heat units	$\frac{40}{21}$	0.281 0708
"	= .8664	kilogr.-Centig., "	$\frac{7}{8}$	$\bar{1}$.937 7368
"	= .0013592	metric horse-power-hour	$\frac{4}{3000}$	$\bar{3}$.133 2698
"	= .0013406	horse-power-hour	$\frac{4}{3000}$	$\bar{3}$.127 2954
1 metric horse-power-hour	= 2648700.	joules		6.423 0327
"	= 1952940.	foot-pounds		6.290 6908
"	= 270000.	kilogram-meters		5.431 3638
"	= 2529.7	pound-Fah., heat units	$\frac{10000}{4}$	3.403 0735
"	= 1405.4	pound-Centig., heat units	$\frac{7000}{5}$	3.147 8010
"	= 637.5	kilogr.-Centig., "	$\frac{5000}{8}$	2.804 4670
"	= 735.75	watt-hours	$\frac{3000}{4}$	2.866 7302
"	= .98634	horse-power-hour	$\frac{80}{81}$	$\bar{1}$.994 0256
1 horse-power-hour	= 2685400.	joules		6.429 0071
"	= 1980000.	foot-pounds		6.296 6652
"	= 273740.	kilogram-meters		5.437 3382
"	= 2564.8	pound-Fah., heat units	$\frac{10000}{4}$	3.409 0479
"	= 1424.9	pound-Centig., heat units	$\frac{10000}{7}$	3.153 7754
"	= 646.31	kilogr.-Centig., "	$\frac{2000}{3}$	2.810 4414
"	= 745.941	watt-hours	$\frac{3000}{4}$	2.872 7046
"	= 1.01385	metric horse-power-hours	$\frac{81}{80}$	0.005 9744

Heat.

1 gram-Centigrade	= .001	kilogram-Centigrade	$\frac{1}{1000}$	$\bar{3}$.000 0000
1 pound-Fahrenheit	= 1047.03	joules	$\frac{2100}{2}$	3.019 9593
"	= 772.	foot-pounds	$\frac{3000}{4}$	2.887 6173
"	= 106.731	kilogram-meters	$\frac{320}{3}$	2.028 2903
"	= .55556	pound-Centigrade	$\frac{5}{9}$	$\bar{1}$.744 7275
"	= .25200	kilogram-Centigrade	$\frac{1}{4}$	$\bar{1}$.401 3935
"	= .29084	watt-hour	$\frac{2}{7}$	$\bar{1}$.463 6567
"	= .0003953	metric horse-power-hour	$\frac{4}{10000}$	$\bar{4}$.596 9265
"	= .0003899	horse-power-hour	$\frac{4}{10000}$	$\bar{4}$.590 9521
1 pound-Centigrade	= 1884.66	joules	$\frac{11000}{6}$	3.275 2318
"	= 1389.6	foot-pounds	$\frac{7000}{5}$	3.142 8898
"	= 192.116	kilogram-meters	$\frac{2100}{11}$	2.283 5628
"	= 1.8000	pound-Fahrenheit	$\frac{9}{5}$	0.255 2725

Heat.—(Continued.)

1 pound-Centigrade	= .4536	kilogram-Centigrade	$\frac{9}{20}$	$\bar{1}.656\ 6660$
"	= .52352	watt-hour	$\frac{11}{21}$	$\bar{1}.718\ 9292$
"	= .0007115	metric horse-power-hour	$\frac{5}{7000}$	$\bar{4}.852\ 1990$
"	= .0007018	horse-power-hour	$\frac{7}{10000}$	$\bar{4}.846\ 2246$
1 kilogram-Centigrade	= 4154.95	joules	$\frac{50000}{12}$	3.618 5658
"	= 3063.5	foot-pounds	3000.	3.486 2238
"	= 423.54	kilogram-meters	$\frac{3000}{7}$	2.626 8968
"	= 3.9683	pound-Fahrenheit	4	.598 6065
"	= 2.2046	pound-Centigrade	$\frac{20}{9}$	0.343 3340
"	= 1.1542	watt-hours	$\frac{8}{7}$	0.062 2632
"	= .001569	metric horse-power-hour	$\frac{8}{5000}$	$\bar{3}.195\ 5330$
"	= .0015472	horse-power-hour	$\frac{3}{2000}$	$\bar{3}.189\ 5586$

Power.

1 erg per second	= .0000001	watt		$\bar{7}.000\ 0000$
1 watt, or	= 10000000.	ergs per second		7.000 0000
1 volt-ampere, or	= 44.2394	foot-pounds per min.	$\frac{88}{2}$	1.645 8093
1 joule per second, or	= 6.11622	kilogram-meters per min.	6.	0.786 4823
1 volt-coulomb per	= .0573048	lb.-Fah., heat unit per min.	$\frac{4}{70}$	$\bar{2}.758\ 1920$
second	= .0318360	lb.-Cent., "	$\frac{7}{220}$	$\bar{2}.502\ 9195$
"	= .0144402	klgr.-Cent., "	$\frac{1}{70}$	$\bar{2}.159\ 5855$
"	= .0013592	metric horse-power	$\frac{4}{3000}$	$\bar{3}.133\ 2698$
"	= .0013406	horse-power	$\frac{4}{3000}$	$\bar{3}.127\ 2954$
1 foot-pound per min.	= 226043.	ergs per second		5.354 1907
"	= .0226043	watt	$\frac{2}{90}$	$\bar{2}.354\ 1907$
"	= .13825	kilogram-meter per min.	$\frac{7}{50}$	$\bar{1}.140\ 6730$
"	= .00003072	metric horse-power	.00003	$\bar{5}.487\ 4605$
"	= .000030303	horse-power	.00003	$\bar{5}.481\ 4861$
1 kilogram-meter per minute	= 1635000.	ergs per second		6.213 5177
"	= .163500	watt	$\frac{1}{6}$	$\bar{1}.213\ 5177$
"	= 7.23314	foot-pounds per minute	$\frac{15}{2}$	0.859 3270
"	= .0002222	metric horse-power	$\frac{2}{9000}$	$\bar{4}.346\ 7874$
"	= .0002192	horse-power	$\frac{2}{9000}$	$\bar{4}.340\ 8130$
1 metric horse-power,	= 735.75×10^7	ergs per second		9.866 7302
or	= 735.750	watts	$\frac{3000}{4}$	2.866 7302
1 French horse-power,	= 32549.0	foot-pounds per minute	$\frac{100000}{3}$	4.512 5395
or	= 4500.	kilogram-meters per min.	$\frac{9000}{2}$	3.653 2125
1 cheval-vapeur, or	= 42.162	lb.-Fah., heat units per min.	$\frac{500}{12}$	1.624 9222
1 force de cheval, or	= 23.423	lb.-Cent., "	$\frac{70}{3}$	1.369 6497
1 Pferdekraft	= 10.625	klg.-Cent., "	$\frac{21}{2}$	1.026 3157
"	= .98634	horse-power	$\frac{80}{81}$	$\bar{1}.994\ 0256$
1 horse-power	= 745.94×10^7	ergs per second		9.872 7046
"	= 745.941	watts	$\frac{3000}{4}$	2.872 7046
"	= 33000.	foot-pounds per minute	$\frac{100000}{3}$	4.518 5139
"	= 4562.33	kilogram-meters per min.	$\frac{9000}{2}$	3.659 1869
"	= 42.746	lb.-Fah., heat units per min.	$\frac{300}{7}$	1.630 8966
"	= 23.748	lb.-Cent., "	$\frac{70}{3}$	1.375 6241
"	= 10.772	klg.-Cent., "	11.	1.032 2901
"	= 1.01385	metric horse-powers	$\frac{81}{80}$	0.005 9744

Power.—(Continued.)

1 lb.-Fah., heat unit per min.	$= 17.45 \times 10^7$	ergs per second		8.241 8080
"	= 17.4505	watts	$\frac{70}{4}$	1.241 8080
"	= .023718	metric horse-power	$\frac{7}{300}$	$\bar{2}$.375 0778
"	= .023394	horse-power	$\frac{7}{300}$	$\bar{2}$.369 1034
1 lb.-Cent., heat unit per min.	$= 31.41 \times 10^7$	ergs per second		8.497 0805
"	= 31.4109	watts	$\frac{1000}{32}$	1.497 0805
"	= .04269	metric horse-power	$\frac{3}{70}$	$\bar{2}$.630 3503
"	= .042109	horse-power	$\frac{3}{70}$	$\bar{2}$.624 3759
1 klgr.-Cent., heat unit per min.	$= 69.25 \times 10^7$	ergs per second		8.840 4145
"	= 69.249	watts	70.	1.840 4145
"	= .09412	metric horse-power	$\frac{2}{21}$	$\bar{2}$.973 6843
"	= .092835	horse-power	$\frac{1}{11}$	$\bar{2}$.967 7099

Circular (Cross-section) Units.*

1 circular mil	= .78540	square mil	$\frac{8}{10}$	$\bar{1}$.895 0899
"	= .00064514	circular millimeter	$\frac{5}{8000}$	$\bar{4}$.809 6518
"	= .00050669	square millimeter	$\frac{1}{2000}$	$\bar{4}$.704 7417
1 square mil	= 1.2732	circular mils	$\frac{10}{8}$	0.104 9101
"	= .00082141	circular millimeter	$\frac{1}{1200}$	$\bar{4}$.914 5619
1 circular millimeter	= 1550.1	circular mils	$\frac{3000}{2}$	3.190 3482
"	= 1217.4	square mils	$\frac{6000}{5}$	3.085 4381
"	= .78540	square millimeter	$\frac{8}{10}$	$\bar{1}$.895 0899
1 square millimeter	= 1973.6	circular mils	2000.	3.295 2583
"	= 1.2732	circular millimeters	$\frac{10}{8}$	0.104 9101
If d is the diameter of a circle, the area in other units is:				
If d is in mils, area in sq. millimeters	$= d^2 \times .00050669$		$\frac{1}{2000}$	$\bar{4}$.704 7417
d in millimeters, area in sq. mils	$= d^2 \times 1217.4$		$\frac{6000}{5}$	3.085 4381
d in centimeters, area in sq. inches	$= d^2 \times .12174$		$\frac{6}{50}$	$\bar{1}$.085 4381
d in inches, area in sq. centimeters	$= d^2 \times 5.0669$		5	0.704 7417

* A circular unit is the area of a circle whose diameter is one unit.

Electrical Resistance.

1 Siemens or mercury unit	= .9540	B. A. unit	$\frac{20}{21}$	$\bar{1}$.979 5312
"	= .9434	legal ohm	$\frac{20}{21}$	$\bar{1}$.974 6941
1 B. A. unit	= 1.0483	Siemens units	$\frac{21}{20}$	0.020 4688
"	= .9889	legal ohm	1.	$\bar{1}$.995 1629
1 legal ohm	= 1.0600	Siemens units	$\frac{21}{20}$	0.025 3059
"	= 1.0112	B. A. units	1.	0.004 8371

Specific Electrical Resistance.				
1 ohm per foot per circ. mil or per mil diam.	= .78540	ohm per foot per sq. mil	$\frac{8}{10}$	$\bar{1}$.895 0899
"	= .16624	microhm per cubic centimeter	$\frac{1}{6}$	$\bar{1}$.220 7346
"	= .0021166	ohm per meter per m. m. diam.	$\frac{21}{10000}$	$\bar{3}$.325 6447
"	= .0016624	ohm per meter per sq. m. m.	$\frac{1}{600}$	$\bar{3}$.220 7346
1 ohm per foot per sq. mil	= 1.2732	ohms per foot per mil diam.	$\frac{10}{8}$	0.104 9101
"	= .21166	microhm per cubic centimeter	$\frac{21}{100}$	$\bar{1}$.325 6447
"	= .0026950	ohm per meter per m. m. diam.	$\frac{8}{3000}$	$\bar{3}$.430 5548
"	= .0021166	ohm per meter per sq. m. m.	$\frac{21}{10000}$	$\bar{3}$.325 6447
1 microhm per cubic centimeter	= 6.0154	ohms per foot per mil diam.	6	0.779 2654
"	= 4.7245	ohms per foot per sq. mil	$\frac{100}{21}$	0.674 3553
"	= .012732	ohm per meter per m. m. diam.	$\frac{1}{80}$	$\bar{2}$.104 9101
"	= .01	ohm per meter per sq. m. m.	.01	$\bar{2}$.000 0000
1 ohm per meter per circular millimeter or per millimeter diam.	= 472.45	ohms per foot per mil diam.	$\frac{10000}{21}$	2.674 3553
"	= 371.06	ohms per foot per sq. mil	$\frac{3000}{8}$	2.569 4452
"	= 78.540	microhms per cubic centimeter	80	1.895 0899
"	= .78540	ohm per meter per sq. m. m.	$\frac{8}{10}$	$\bar{1}$.895 0899
1 ohm per meter per sq. millimeter	= 601.54	ohms per foot per mil diam.	600.	2.779 2654
"	= 472.45	ohms per foot per sq. mil	$\frac{10000}{21}$	2.674 3553
"	= 100.	microhms per cubic centimeter	100.	2.000 0000
"	= 1.2732	ohms per meter per m. m. diam.	$\frac{10}{8}$	0.104 9101
Electrical Quantity.				
1 coulomb	= .0002778	ampere-hour	$\frac{3}{11000}$	$\bar{4}$.443 6975
1 ampere-hour	= 3600.	coulombs		3.556 3025

Absolute Electrical Units.

1 coulomb	= 10^{-1}	electromagnetic units of	quantity
1 ampere	= 10^{-1}	"	"	current
1 volt	= 10^{8}	"	"	e. m. f.
1 ohm	= 10^{9}	"	"	resistance
1 farad	= 10^{-9}	"	"	capacity
1 joule	= 10^{7}	absolute units of work (ergs)		
1 watt	= 10^{7}	absolute units of power (ergs per second)		
1 micro——	= 1 millionth			
1 mega——	= 1 million			
1 foot-pound 1 kilogram-meter 1 metric horse-power 1 horse-power	= = = =	See ergs and ergs per second in tables of Work and Power.		

"Dimensions" of Mechanical, Electrical and Magnetic Units.

m = mass, l = length, t = time.

Surface	l^2
Volume (capacity)	l^3
Velocity	$l\,t^{-1}$
Acceleration	$l\,t^{-2}$
Force	$m\,l\,t^{-2}$
Weight	$m\,l\,t^{-2}$
Work or heat (joule, foot-lbs. or heat units)	$m\,l^2\,t^{-2}$
Power (rate of work, watt, horse-power)	$m\,l^2\,t^{-3}$
Electrical quantity *	$m^{\frac{1}{2}}\,l^{\frac{1}{2}}$
Current*	$m^{\frac{1}{2}}\,l^{\frac{1}{2}}\,t^{-1}$
Electromotive force *	$m^{\frac{1}{2}}\,l^{\frac{3}{2}}\,t^{-2}$
Resistance *	$l\,t^{-1}$
Capacity *	$l^{-1}\,t^2$
Magnetic quantity (magnetic lines of force)	$m^{\frac{1}{2}}\,l^{\frac{3}{2}}\,t^{-1}$
Magnetic intensity	$m^{\frac{1}{2}}\,l^{-\frac{1}{2}}\,t^{-1}$

* In the electromagnetic system.